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REPORT NO. 640/218-2
WATERTOWN ARSENAL

American Car and Foundry Division
ACF Industries, Incorporated
Research and Development

Weldability of Rare Earth Treated Homogeneous Armor Steel Plate
Interim Report No. 2

Contract No. DA-36-034-ORD-1423RD

May 9, 1955 Major Report No. 207A

by
William G. Smith

Approved by: George Reed

Approved by: J. M. Gruitch

Major Report No. 207A

INTERIM REPORT NO. 2

Contractor:	ACF Industries, Incorporated
Contract Number:	DA-36-034-ORD-1423RD
Title of Report:	Weldability of Rare Earth Treated Homogeneous Armor Steel Plate. Interim Report No. 2.
File Number:	WAL 642/218-2
Date:	May 9, 1955
Agency:	Army Ordnance Department, Watertown Arsenal
Technical Supervision:	Watertown Arsenal Laboratory
Ordnance District:	Philadelphia
Author:	William G. Smith
Object:	To determine the relative weldability of rare earth metal treated, rare earth oxide treated, and normal production manganese-molybdenum composition wrought homogeneous armor steels.

Summary:

This report covers the steel mill operating records and the laboratory phases of the investigation, including chemical analysis, microstructure and microhardness, hardenability determinations, examination of gas cut edges for cracks and hardness, bend testing, impact testing (plate and weld deposit transition curves) and fatigue testing. A comparison is made between the top and bottom of each ingot involved. Also a sonic method of detecting cracks during welding is evaluated.

The fabrication and welding of a series of test plates was covered in Interim Report No. 1. A final report summarizing the two interim reports and giving the results of explosion bulge and ballistic tests will be issued later.

Conclusions:

Steel mill operating records and chemistry determinations indicate differentials which are reflected in all laboratory tests with basic materials of higher chemistry being of higher hardenability and lower ductility. The sulfur content of the rare earth metal treated heat was found to be unusually low, however, the shape of the sulfide inclusions had not been altered by the rare earth addition. The sulfur content of the rare earth oxide treated heat was normal and the shape of the sulfide inclusions was unaltered. The rare earth metal treated heat exhibited improved impact strength in contrast to the subnormal values of the other two heats.

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Introduction

1. For the past number of years wrought homogeneous armor of 1/2-inch thickness has exhibited a tendency for low or borderline toughness qualities. In an effort to overcome this condition, a number of armor heats have been treated with additions of rare earth elements and the use of such armor in the production of armored vehicles has resulted in some fabricators claiming that the tendency for cracking is promoted in the weld fusion and heat affected zones. Variations in notch impact toughness values obtained on the base material and claims of impaired weldability resulted in the Watertown Arsenal Laboratory being requested by the Ordnance Advisory Committee on the Welding of Armor to determine the physical and weldability characteristics of rare earth treated wrought homogeneous armor steel.

2. A portion of the investigative work covering a study of the relative weldability of three heats of armor was contracted to ACF Industries. One heat had been treated with rare earth metals, a second with rare earth oxides and the third was an untreated production heat. The armor steel was of the manganese-molybdenum type, one-half inch in thickness, and was produced by the Jones and Laughlin Steel Corporation.

Scope of Investigation

3. The fabrication and welding of a series of test plates prepared for the evaluation of the weldability, explosion bulge and ballistic properties of the three materials was discussed in Interim Report No. 1. The relative weldability of the three materials as determined on the basis of weld soundness was also covered in Interim Report No. 1.

4. It is the purpose of this Interim Report No. 2 to cover the steel mill operating records and the laboratory phases of the investigation including chemical analysis, microstructure and microhardness, hardenability determinations, examination of gas cut edges for cracks and hardness, bend testing, impact testing (plate and weld deposit transition curves) and fatigue testing with a comparison being made between the top and bottom of each ingot involved. Also a sonic method of detecting cracks during welding is evaluated.

5. A final report will be issued summarizing these two interim reports and including the results of explosion bulge tests and ballistic tests to be conducted on the plates prepared and reported on in Interim Report No. 1.

Material

6. For purposes of this investigation the following plate material was procured from the Watertown Arsenal and the Jones and Laughlin Steel Corporation, all material having been produced by the Jones and Laughlin Steel Corporation:

A. From heat JL 0681 with rare earth metal addition:

5 plates 1/2" x 68" x 108" from Ingot 1, cuts 1, 2 and 5.
3 plates 1/2" x 37" x 42" from Ingot 2, cut 1 (for "H" plates only).

B. From heat JL 0724 with rare earth oxide addition:

3 plates 1/2" x 37" x 42" from Ingot 2, cut 2 (for "H" plates only).
4 plates 1/2" x 57" x 196" from Ingot 3, cuts 1, 2, 4 and 5.

C. From heat JL 0823, normal production armor:

5 plates 1/2" x 71" x 101-3/8" from Ingot 3, cuts 1, 2 and 5.
3 plates 1/2" x 37" x 42" from Ingot 3, cut 3 (for "H" plates only).

Results

Mill Operating Records

7. The steel mill operating records as furnished by the Jones and Laughlin Steel Corporation for the three heats involved are contained in Tables I, II, III. Rare earth metal treated heat JL 0681 and rare earth oxide treated heat JL 0724 were made as 50-ton heats while normal production armor heat JL 0823 was made as a 200-ton production heat. Methods of making slag, making furnace additions, blocking of the heat and making ladle additions show variances in steel making practice.

8. Rare earth metal additions were made to heat JL 0681 by the use of "Lanceramp", a product of the American Metallurgical Products Company with an analysis of 45-50% cerium, 30% minimum lanthanum and the balance other rare earth elements plus iron. Rare earth oxide additions were made to heat JL 0724 by the use of "T" compound as produced by the Molybdenum Corporation of America, an intimate mixture of rare earth oxides, a reducing agent and an energizer. Boron was added as a ladle addition in the form of Borosil and X-79 Grainal to heats JL 0681 and JL 0823 respectively, however, no boron addition was made to rare earth oxide treated heat JL 0724. The Jones and Laughlin Steel Corporation maintains that the analysis used for one-half inch homogeneous armor plate is of sufficiently high hardenability that boron is not required when the entire heat is used for plate of one-half inch or less in thickness. Apparently heat JL 0724 was scheduled for one-half inch or less plate so no boron was added.

Chemical Composition

9. With the exception of plates furnished for use as "H" plates only, the chemical composition of the top and bottom cuts of each ingot of each of the three heats involved was determined and is listed in Table IV. The ladle analyses and the established chemical range for Jones and Laughlin Steel Corporation armor of one-quarter to three-quarter inch thickness are also listed. While all determinations, except one, are within the established composition range, the carbon content of the top and bottom cuts of heat JL 0681, ingot 1, and the top cut of heat JL 0823, ingot 3, approach the maximum permissible and, therefore, cannot be considered average. The carbon content of the bottom cut of heat JL 0823, ingot 3, is lower than normal and the carbon contents of the top and bottom cuts of heat JL 0724, ingot 3, are average. The molybdenum content of heat JL 0823 is below average with the ladle analysis .01% below the minimum of the established range.

10. The sulfur contents of .010 and .014 as determined on rare earth metal treated heat JL 0681 are exceptionally low based on ACF's experience extending over eighty-six Jones and Laughlin armor heats which averaged .0198% sulfur with a low of .014% and a high of .030% sulfur. Sulfur reductions of at least .005% are claimed to be directly attributable to additions of Lanceramp[1]; however, as no samples for chemistry were obtained prior to the ladle addition of the rare earth compounds no definite conclusions concerning the effect of the rare earths on the chemical analyses of these heats can be reached.

Hardenability

11. As the plates under test were one-half inch in thickness it was impossible to prepare standard size Jominy end quench specimens, so one-half inch substandard size

1 - Iron Age, April 24, 1952, Page 132.

Results (Cont'd.)

specimens were used for all hardenability tests. The size of orifice and free height of water column of the quenching arrangement were in accordance with SAE recommended practice for the substandard specimen. Specimens were normalized at 1650° F and quenched from 1625° F in conformance with normal production armor heat treating practices. All tests were made in duplicate.

12. Figures 1 to 3 inclusive are graphs showing the end quench hardenability data on the three heats of armor. Specimens from the No. 1 (top) cuts of the rare earth metal treated heat JL 0681 and the normal production heat JL 0823 indicate high hardenability with hardnesses of 50.5 and 48.5 R_c, respectively, at a depth of 32/16-inch. These values reflect the higher carbon and molybdenum contents of heat JL 0681 and the high carbon content of the No. 1 cut of heat JL 0823. The lower carbon and manganese contents and the absence of boron is reflected in the lower end quench hardenability values, 45.5 R_c at 16/16-inch and 33 R_c at 32/16-inch, indicated by specimens from rare earth oxide treated heat JL 0724. On all three heats the hardenability of specimens taken from the ingot bottom cuts was found to be below that determined for specimens from the top cuts.

13. Rare earth elements are not added to steel to alter hardenability although under certain propitious conditions complex rare earth carbides may be formed and hardenability thereby increased.

14. Figures 1, 2 and 3 also show the Jominy end quench hardenability of the three heats as reported by the Jones and Laughlin Steel Corporation. These determinations were made with full size (1-inch) specimens taken from slabs representing the middle of the middle ingot and, therefore, cannot be directly correlated with the values obtained on the 1/2-inch diameter substandard specimens. Jones and Laughlin values indicate heats JL 0724 and JL 0823 to be of similar hardness at 8/16-inch which is not in conformance with ACF results which indicate JL 0724 to be of lower hardness. Jones and Laughlin results also indicate heats JL 0724 and JL 0823 as having like hardnesses at 32/16-inch and that this hardness is higher than that found for JL 0681 at a like depth. ACF results indicate high hardness of JL 0681 at 32/16-inch with JL 0823 being only slightly lower and JL 0724 being quite low at the same depth.

Microstructure

15. Specimens were taken from the top and bottom cuts of each ingot for the evaluation of microstructure and the size and distribution of sulfide inclusions. Figures 4, 5 and 6 show typical sulfide inclusions present in the bottom cut of ingots from rare earth metal treated heat JL 0681, the rare earth oxide treated heat JL 0724, and normal production heat JL 0823, respectively. All specimens were etched with boiling alkaline sodium picrate for identification of sulfide inclusions by removal. The sulfide inclusions present in all specimens were of the stringer type and generally of the same nature. The quantity observed followed the amount detected in the chemical analyses. There was, therefore, no noticeable effect of the rare earth additions on the shape or type of sulfide inclusions.

16. Microstructures of the three heats are shown by Figures 7, 8 and 9 (heats JL 0681, JL 0724 and JL 0823 respectively) and indicate that the structures are typical tempered martensite with the top cuts of ingots from heats JL 0681 and JL 0823 exhibiting a finer dispersion than the bottom cuts of the same ingots or both cuts of heat JL 0724. Grain boundaries are heavier and more distinct on specimens from heat JL 0724 and general grain

Results (Cont'd.)

size is larger which normally increases hardenability, however, this heat was found to be lower in hardenability than either of the other two heats because the carbon and manganese contents are lower and no boron was added.

Microhardness

17. The hardnesses of base plate material, weld heat-affected zones, weld fusion zones and weld deposits were determined on the top and bottom cuts of each ingot involved on each heat by means of microhardness studies. For this purpose, cross sections were taken through 1/4-inch fillet welds joining 1/2" x 2" x 10" to 1/2" x 10" x 20" plates in a lap joint fashion. The welding of the specimens was accomplished in one pass using 3/16-inch diameter class 230 low hydrogen ferritic electrodes conforming to Specification MIL-E-986A and with a welding current of 210 amperes at 23 volts.

18. Cross section specimens, after polishing, were lightly etched with nital for the identification of weld zones, and hardness readings were taken across unaffected plate material and the weld deposit in a line at 45° with the bottom of the original plate. All determinations were made on an Eberhard Microhardness Tester with readings being taken .005-inch apart.

19. Figures 10, 11 and 12 are graphs showing the Vickers hardness numbers determined on cross sections of the weldments made on plates from the top and bottom cuts of the three materials under investigation. The hardenability of the three heats as ascertained by end quench specimens and previously discussed is reflected by the microhardness values determined on the heat-affected zones. The highest hardnesses occurred on specimens from rare earth metal treated heat JL 0681, intermediate hardnesses on the top cut of normal production armor heat JL 0823 and lowest hardnesses on rare earth oxide treated heat JL 0724 and the bottom cut of heat JL 0823. Specimens from top and bottom cuts of low hardenability heat JL 0724 and from the bottom cut of heat JL 0823 had hardnesses of 250-260 VHN at the base of the heat-affected zone, the other three specimens had hardnesses of 274-288 VHN at this location.

Gas Cut Edges

20. All plates prepared for this investigation were gas cut in accordance with ACF standard procedure, using No. 2 Airco series 138 burning tips and gas pressures of five pounds of acetylene and 45 pounds of oxygen. All edges were visually examined and a number of edges were magnafluxed for the presence of edge cracks; none was found.

21. For the determination of gas cut edge hardnesses 4" x 10" plates were gas cut from the top and bottom cuts of ingots of the three heats. A 6-inch long 1/2-inch high specimen was cut from each of the six plates and one cut edge of each specimen was surface ground in such a manner that the surface tapered 3/16-inch from the gas cut edge, the original edge being undisturbed at one end of the specimen. In this manner a long angular slice through the gas cut edge heat-affected zone was obtained and it was possible to determine the exact depth of any point from the original surface by calculations based on the angle of taper and the distance from the end of the taper. Hardness readings using the Rockwell "A" scale were taken at 1/8-inch increments along the tapered surface. Three lines of readings were taken, 1/16-inch from top surface (as cut), at the center, and 7/16-inch from top surface (1/16-inch from bottom).

Results (Cont'd.)

22. Figures 13 through 18 inclusive are plots of the hardness values determined. Evaluation of the data on the basis of hardness levels at various depths indicates the following:

A. Edge hardness is highest on rare earth metal treated heat JL 0681, intermediate on normal production heat JL 0823, and lowest on rare earth oxide treated heat JL 0724.

B. The heat-affected zone is of similar depth on heats JL 0681 and JL 0823 and shallower on heat JL 0724.

C. The ingot top and bottom cuts of each heat have similar edge hardness patterns.

23. The values agree with the results of the end quench hardenability tests. Previous experimental work has indicated edge hardnesses of 490 BHN and over as being high for 1/2-inch plate gas cut by this procedure and the high and borderline hardenabilities of heats JL 0681 and JL 0823 are again indicated.

Bend Tests

24. To ascertain any variation of ductility in cold forming, bend tests were made on specimens from the top and bottom cuts of each of the three heats. The specimens were 2-1/2-inches wide by 10-inches long and with orientation such that the axis of bend was perpendicular to the final rolling direction. All specimens were surface ground (about .015-inch metal removal) on both sides and one side was very lightly scribed at 1/8-inch intervals for determination of elongation. Bending was accomplished around a pin having an approximate radius of one and one-half times the plate thickness (1-1/2-inch diameter) with all bends being taken to the point of plate failure. Elongation for each 1/8-inch increment was then determined and this data is graphically shown in Figures 19, 20 and 21.

25. The bend tests on heats JL 0681 and JL 0823 indicate similarity with failure points of specimens from the ingot top cuts at 32 and 37% elongation and failure points of specimens from the bottom cuts at 25 and 22% elongation, respectively. Specimens from heat JL 0724 indicate the lower chemistry and hardness with the failure points being at 45 and 40% elongation.

Impact Tests

26. Notch toughness values at normal and subnormal temperatures were determined for base plate and weld deposits on each of the three heats. The notch toughness and transition temperature values of the heat-affected zone are to be determined by the Rensselaer Polytechnic Institute under separate contract with the Watertown Arsenal and plate material from a similar ingot location on each of the three heats has been furnished Rensselaer for this purpose.

27. All notch toughness values were determined by means of standard V-notch Charpy impact tests. Specimens for test of the base plate material were cut with orientation of notch in accordance with the requirements of Specification MIL-A-12560 (ORD), dated March 9, 1953, i.e., specimens were cut in a direction such that the fracture face was

Results (Cont'd.)

parallel to the direction of major ratio of reduction in gage during rolling, and with the V-notch cut perpendicular to the plate surface. A Riehle Pl-2 combination standard impact machine was used for all impact work and duplicate specimens were broken at room temperature, 0° F, -40° F, -60° F, -80° F and -100° F. The specimens were cooled to the desired temperature in a mixture of dry ice and methyl alcohol and the temperatures were maintained for a minimum of fifteen minutes prior to test. All specimens were broken within five seconds after removal from the cooling medium.

28. Figures 22, 23 and 24 are plots of the notch toughness values determined on the plate material from each heat. At all temperatures, notch toughness values ascertained for rare earth metal treated heat JL 0681 are superior to those of either rare earth oxide treated heat JL 0724 or normal production heat JL 0823. As shown by Figure 22, at -40° F, specimens from heat JL 0681 had notch impact strengths of 17.5 and 14 ft-lbs on cut 1 (top) and 19 and 21 ft-lbs on cut 5 (bottom). As the hardnesses on these impact specimens were 363 and 352 BHN, respectively, 15.1 and 16.7 ft-lbs would be required for material acceptance under Military Specification MIL-A-12560 (ORD). As shown by Figures 23 and 24, specimens from heats JL 0724 and JL 0823, with the exception of cut 5, heat JL 0823, which indicated higher values at room temperature and 0° F, exhibit similar notch impact values at all temperature levels. Impact specimens from both heats exhibited borderline low hardness values with specimens from heat JL 0724 being 335-341 BHN and those from JL 0823 being 343-343 BHN. Specification impact requirements at these hardness levels range from 18.2 to 19.8 ft-lbs so both heats fail to meet minimum prescribed limits. Jones and Laughlin reported the following impact values, (1) heat JL 0681 at 20.4 ft-lbs with 375 BHN, (2) heat JL 0724 at 18.5 ft-lbs with 363 BHN, (3) heat JL 0823 at 14.5 ft-lbs with 363 BHN. These values are acceptable.

29. The plots of notch toughness values indicate transition temperatures as determined by Charpy V-notch impact, and measured by the change in slope of the curve rather than at the 15 ft-lb level, to be:

A. Top cuts of heats JL 0681 and JL 0724 at a temperature less than 0° F and greater than -40° F.

B. Bottom cuts of heats JL 0681 and JL 0724 at a temperature less than -40° F and greater than -60° F.

C. Both top and bottom cuts of heat JL 0823 at a temperature less than 0° F and greater than -40° F.

30. In conjunction with the notch impact tests, ductility determinations were made by measurement of the reduction in cross-section dimension at the point of fracture. The values measured, Figures 22, 23 and 24, indicate the fractures at all temperatures to possess some degree of ductility and that the condition of completely brittle fracture does not occur at any temperature in excess of -100° F.

31. Notch toughness values of welds joining plates of the three materials were made on weld deposits of double vee weldments of plates from the top cuts of each of the three heats. All welds were made with 45° included angle and 3/16-inch root opening using Tensilend 100 low hydrogen ferritic electrodes. Notches were cut for Charpy V-notch impact tests transverse to the weld deposit and perpendicular to the plate surfaces. Figure 25 is a plot showing the values obtained for the three welds and indicating impact values declining from 40-50 ft-lbs at room temperature to 7-15 ft-lbs at -80° F. A transition

Results (Cont'd.)

temperature of -50°F is indicated for the weld metal joining plates of rare earth oxide treated heat JL 0724, however, no definite transition point is apparent for the weld metal joining the other two materials.

Fatigue Tests

32. A fatigue test previously developed by ACF Industries was used to obtain a comparison of the fatigue strengths of the three materials in area of weld deposits. This test procedure involved the imposition of tension stresses of fatigue level at the toe of fillet welds by means of repetitious application of load to the free end of a cantilever type specimen. This design of specimen is sensitive to variations of geometric conditions at the toe of the fillet weld and these conditions are made as constant as possible.

33. Specimens for the test were cross sections taken through 1/4-inch fillet welds joining 1/2" x 2" x 10" to 1/2" x 10" x 16" plates in a lap joint. The welding of the samples was accomplished in one pass using 3/16-inch diameter class 230 (Tensilend 100) low hydrogen ferritic electrodes conforming to Specification MIL-E-986A and with a welding current of 210 amperes at 23 volts. Three 2-inch wide by 16-inch long fatigue test specimens were cut from each plate by means of an abrasive cut-off wheel and edges were cleaned by emery cloth and corners in area of weld were radiused to 1/16-inch by filing and polishing. Figure 26 shows a specimen with an SR-4 strain gage applied for detection of initiation of failure and with a manganese steel wear plate applied to the opposite end for contact with the rotating cam loading mechanism.

34. Figure 27 shows the test equipment with three specimens in position for test. The specimens are mounted in adjustable inclined plate support blocks in such a manner that proper height is attained and the toe of the fillet weld is at the point of maximum stress. Load is applied to the free end of the specimens by means of cams attached to a rotating shaft and tension stresses are imposed at the toe of the weld, with each revolution of the shaft causing one cycle of flexure. The magnitude of the load and the stress in the test piece are controlled by cam size and resultant displacements. The fatigue tests were run at an approximate speed of 1150 rpm with the number of cycles of imposed stress recorded by a cycle counter attached to the end of the cam shaft. Figure 28 shows an over-all view of the test setup.

35. To obviate the necessity of frequent stopping of the machine and removal of test specimens for detection of the initiation of failure, a recording system utilizing the SR-4 strain gages connected to an automatic multiple point recorder was used. The strain gages were attached to the test specimens at a location tangent to the toe of the fillet weld where all failures took place so that any alteration of stress level by failure was immediately indicated on the multiple point recorder.

36. The specimens were tested at 28,000 and 35,000 psi stress levels as previous investigations of the fatigue strength of fillet welded joints of the same type had indicated these values to be at the knee of the S-N curve. The stress levels imposed required specimen deflections of 1/4-inch and 5/16-inch respectively.

37. Figure 29 is a graph showing fatigue strength values determined for the three materials in the area of weld deposits. In the absence of notches, fatigue strength is proportional to tensile strength and hardness and this is reflected in the higher values

Results (Cont'd.)

found for the specimens from the higher hardenability rare earth metal treated heat JL 0681 (specimens A1 and A29) and the top cut of the normal production heat JL 0823 (specimen C1). Specimens from the rare earth oxide treated heat JL 0724 (specimens B1, B57 and B115, top and bottom cuts of ingot) showed intermediate to low values and specimens from the bottom cut of the ingot from JL 0823 (specimen C116) which exhibited low chemistry and low hardenability were found to have the lowest fatigue strength. These trends, even though the result of limited testing, correlate with the variations in hardness of weld deposit heat-affected zones found by the microhardness determinations.

Sonic Method of Crack Detection

38. Previous ACF investigation of cracking in welds and weld heat-affected zones during and immediately subsequent to welding of one-half inch homogeneous armor plate led to attempts to develop a sonic pickup system for detection of cracking on occurrence. Equipment used in these previous tests consisted of a crystal pickup unit in contact with the plate, an amplifying system, and a speaker. The results of these preliminary tests were encouraging and indicated that the method was potentially practical.

39. In an effort to further develop and evaluate the use of this method of detection of cracks, a number of welds were made using an oscillograph in conjunction with a crystal pickup unit and a sound level meter which was used as a preamplifier. This system would have permitted recording of the time of cracking for correlation with plate temperatures but it did not prove satisfactory as extraneous noises created "hash" on the oscillograph trace which marked crack indications beyond definite recognition. Therefore, the original arrangement of apparatus was again used with the exception that a magnetic pickup unit was substituted for the cyrstal pickup unit. A photograph of a typical test setup is included as Figure 30 and a schematic diagram is shown in Figure 31.

40. With this later apparatus the occurrence of cracks in test plates subsequent to welding was audibly detectable, however, the number of cracks occurring in any single weldment could not be determined with certainty as all cracks formed in a progressive manner with a series of noise indications and in the event of multiple cracks the source of individual indications was not always apparent.

41. For the final control tests, root passes were deposited in four slot type weldability test samples of one-half inch homogeneous armor having a 45° included angle, double bevel and one-eighth inch root opening. For intentional promotion of cracking an AWS 6011 type electrode was used on one sample. Two plates were welded with low hydrogen electrodes but using AC current at low amperage to promote cracking in a weld deposit of small cross section. Cracking was sonically detected on each of these three tests. One plate was welded with normal welding procedure and with no sonic indication of cracking.

42. The four plates were then radiographed after welding with the result that the three plates on which there was sonic indication of cracking also showed multiple cracks in the X-ray films while the plate which did not indicate cracking by the sonic method did not show cracks on radiographing. It was thus indicated that the method is a practical one which may have wide application in laboratory studies of the weldability characteristics of different materials.

Discussion

43. The laboratory investigation of the three heats of homogeneous armor steels used

Discussion (Cont'd.)

for the determination of the relative weldability of rare earth metal treated, rare earth oxide treated, and normal production manganese-molybdenum composition armor steels indicates differences in steel making practices and variances of chemical composition between heats and between the top and bottom cuts of the ingots from which material was taken for test. Plates from rare earth metal treated heat JL 0681 and the top ingot cut of normal production armor heat JL 0823 were found to have carbon contents approaching the maximum permissible by specification and plates from the rare earth oxide treated heat JL 0724 and bottom ingot cut of normal production heat JL 0823 were of medium to low carbon content. Manganese and molybdenum contents were also at variance. Boron was added to the rare earth metal treated heat JL 0681 and the normal production armor heat JL 0823 but was omitted from the rare earth oxide treated heat JL 0724.

44. These variations in composition and manufacture were reflected in the higher chemical composition material indicating higher end quench hardenability, higher hardness of weld heat-affected zones and higher hardness of gas cut edges. Lower hardenability material was found to be of lower hardness and to exhibit increased ductility as indicated by bend tests.

45. Low sulfur content and improved Charpy V-notch impact properties of rare earth metal treated heat JL 0681 indicate an improvement of steel quality by this type addition. The addition of rare earth oxides caused no observed alteration of chemistry, structure or physical properties. No marked change of transition temperature was found for any condition.

46. Higher hardenability material (top and bottom cuts JL 0681 and top cut of JL 0823) revealed a tendency for greater fatigue strengths in weld areas.

Table I

Mill Operating Record
Heat 0681 - Rare Earth Treated

Open hearth charge:
50,000 lbs. heavy melting molybdenum scrap
40,000 lbs. cold pig iron

Flux charge:
5,100 lbs. limestone
2,600 lbs. burnt lime

Furnace additions:
1,000 lbs. burnt lime
300 lbs. fluorospar
180 lbs. molybdic oxide
750 lbs. ore

Furnace block:
1,450 lbs. silico-manganese
850 lbs. 11% ferro-silicon
850 lbs. ferro-manganese

Ladle additions:
120 lbs. calcium-silicide
80 lbs. lanceramp
72 lbs. aluminum
60 lbs. borosil

The heat was poured into 27" x 52" big end up hot-topped molds and the ingots were rolled into 46" x 4" slabs which were slow cooled from 1750° F to 600° F in 76 hours and were then conditioned by flame scarfing at 300° F to 600° F.

Heat treatment:

Austenitizing furnace	1/2 hour hold at 1650° F water quench
Tempering furnace	1-1/4 hours hold at 875° F water quench

Table II

Mill Operating Record
Heat 0724 - Rare Earth Oxide Treated

Open hearth charge:
- 50,000 lbs. heavy melting molybdenum scrap
- 40,000 lbs. cold pig iron

Flux charge:
- 5,100 lbs. limestone
- 300 lbs. burnt lime

Furnace additions:
- 400 lbs. burnt lime
- 700 lbs. fluorospar
- 480 lbs. molybdic oxide

Furnace block:
- 300 lbs. 11% ferro-silicon
- 250 lbs. silico-manganese
- 2,250 lbs. ferro-manganese

Ladle additions:
- 200 lbs. ferro-manganese
- 130 lbs. rare earth oxide (T compound)
- 80 lbs. 50% ferro-silicon
- 400 lbs. alsifer

The heat was poured into 27" x 52" big end up hot-topped molds and the ingots were rolled into 48-1/2" x 4-1/2" slabs which were slow cooled from 1550° F to 600° F in 72 hours and were then conditioned by flame scarfing at 300° F to 600° F.

Heat treatment:

Austenitizing furnace	1/2 hour hold at 1650° F water quench
Tempering furnace	1-1/4 hours hold at 850° F water quench

Table III

Mill Operating Record
Heat 0823 - Untreated

Open hearth charge:
170,000 lbs. heavy melting molybdenum scrap
38,000 lbs. ore
223,000 lbs. hot metal

Flux charge:
25,600 lbs. limestone

Furnace additions:
8,100 lbs. burnt lime
11,000 lbs. scale
1,200 lbs. molybdenum as molybdic oxide
20,000 lbs. iron jigger (1 hour prior to block)
Residual alloys:
.16% Mo. .04% Cu.
.02% Ni. .02% Cr.

Furnace block:
1,000 lbs. silico-manganese
1,200 lbs. 11% ferro-silicon
8,500 lbs. ferro-manganese
(heat blocked at 2915° F - .09% C)

Ladle additions:
350 lbs. medium carbon-manganese
1,000 lbs. regular manganese
720 lbs. X-79 grainal
1,100 lbs. alsifer

The heat was poured into 27" x 50" big end up hot topped molds and the ingots were rolled into 48" x 4-1/2", 43-1/2" x 4", and 38-1/2" x 4" slabs. The slabs were slow cooled from 1370° F to 650° F in 78 hours and were conditioned by flame scarfing at 300° F to 600° F.

Heat treatment:

Austenitizing furnace	1/2 hour hold at 1650° F water quench
Tempering furnace	1-1/4 hours hold at 860° F water quench

Table IV

Chemical Analyses
(in %)

Heat	Ingot	Cut	TC	Mn	P	S	Si	Ni	Cr	Mo
JL 0681	1	1	0.32	1.70	.014	.014	0.26	0.02	0.05	0.47
JL 0681	1	5	0.29	1.66	.015	.010	0.28	0.02	0.05	0.46
JL 0681*			0.30	1.63	.016	.013	0.29	ND	ND	0.44
JL 0724	3	1	0.27	1.59	.012	.024	0.15	0.03	0.02	0.46
JL 0724	3	5	0.25	1.58	.013	.019	0.18	0.03	0.03	0.44
JL 0724*			0.25	1.53	.010	.022	0.20	ND	ND	0.44
JL 0823	3	1	0.30	1.71	.020	.024	0.17	0.01	0.03	0.40
JL 0823	3	5	0.23	1.66	.017	.018	0.18	0.01	0.02	0.42
JL 0823*			0.27	1.68	.020	.023	0.20	ND	ND	0.39
J&L established range, 1/4" to 3/4" incl.			.22 / .32	1.45 / 1.85	.04 max.	.04 max.	.10 / .30			.40 / .55

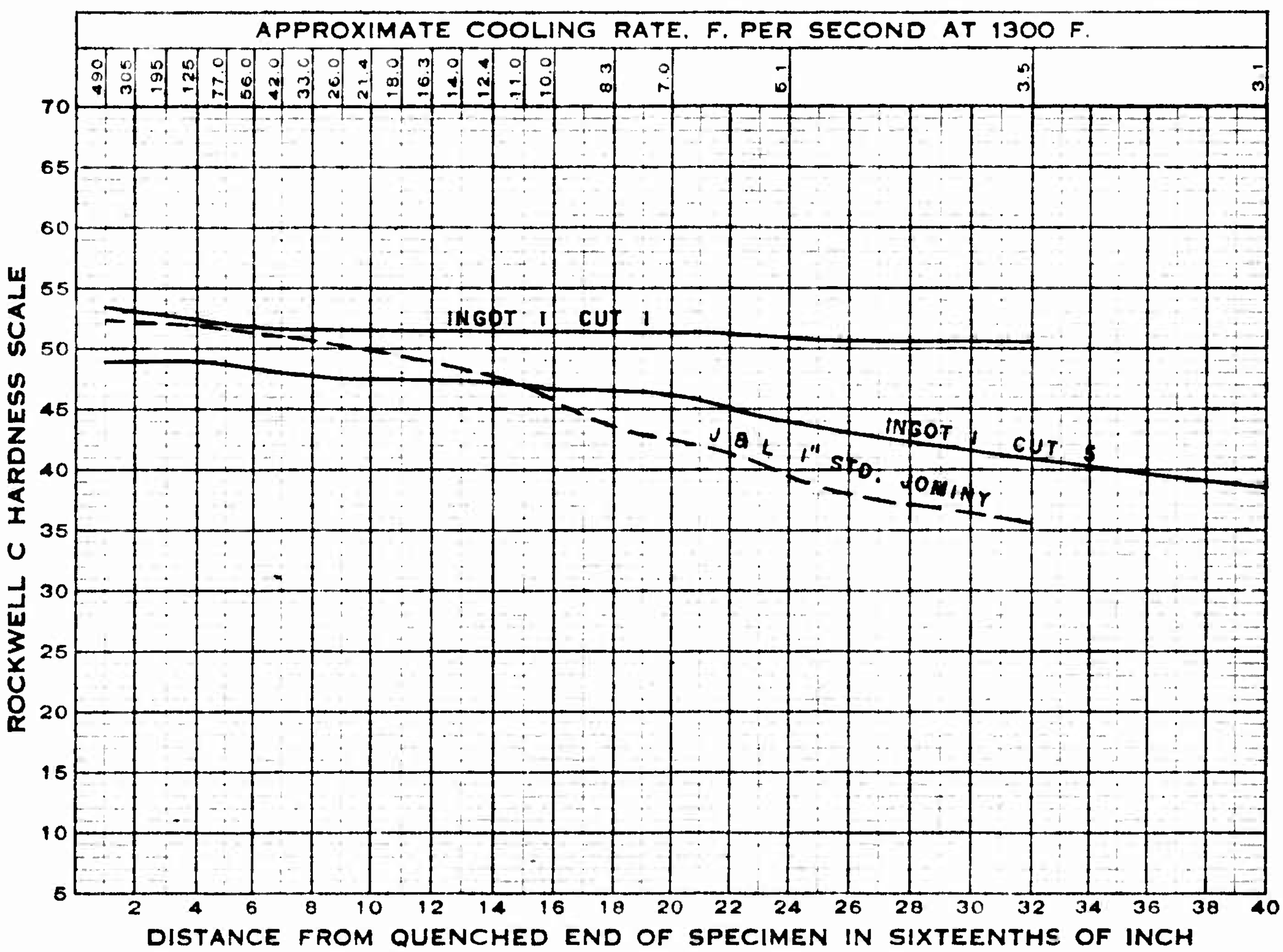
* Jones & Laughlin ladle analyses.
ND Not determined.

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 48 T)

DATE 5-17-54
LABORATORY ACF
TYPE SPECIMEN 1/2" D (SAE)
TEST NO.

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F	QUENCH TEMP. °F
ARMOR	JL 0681		.32	1.70	.014	.014	.26	.02	.05	.47		1650	1625
	ING. I CUT I												
ARMOR	JL 0681		.29	1.66	.015	.010	.28	.02	.05	.46		1650	1625
	ING I CUT 5												

REMARKS:



AMERICAN SOCIETY FOR TESTING MATERIALS
1916 RACE ST. PHILADELPHIA 3, PA.

Figure I
END QUENCH HARDENABILITY DATA
HEAT JL 0681

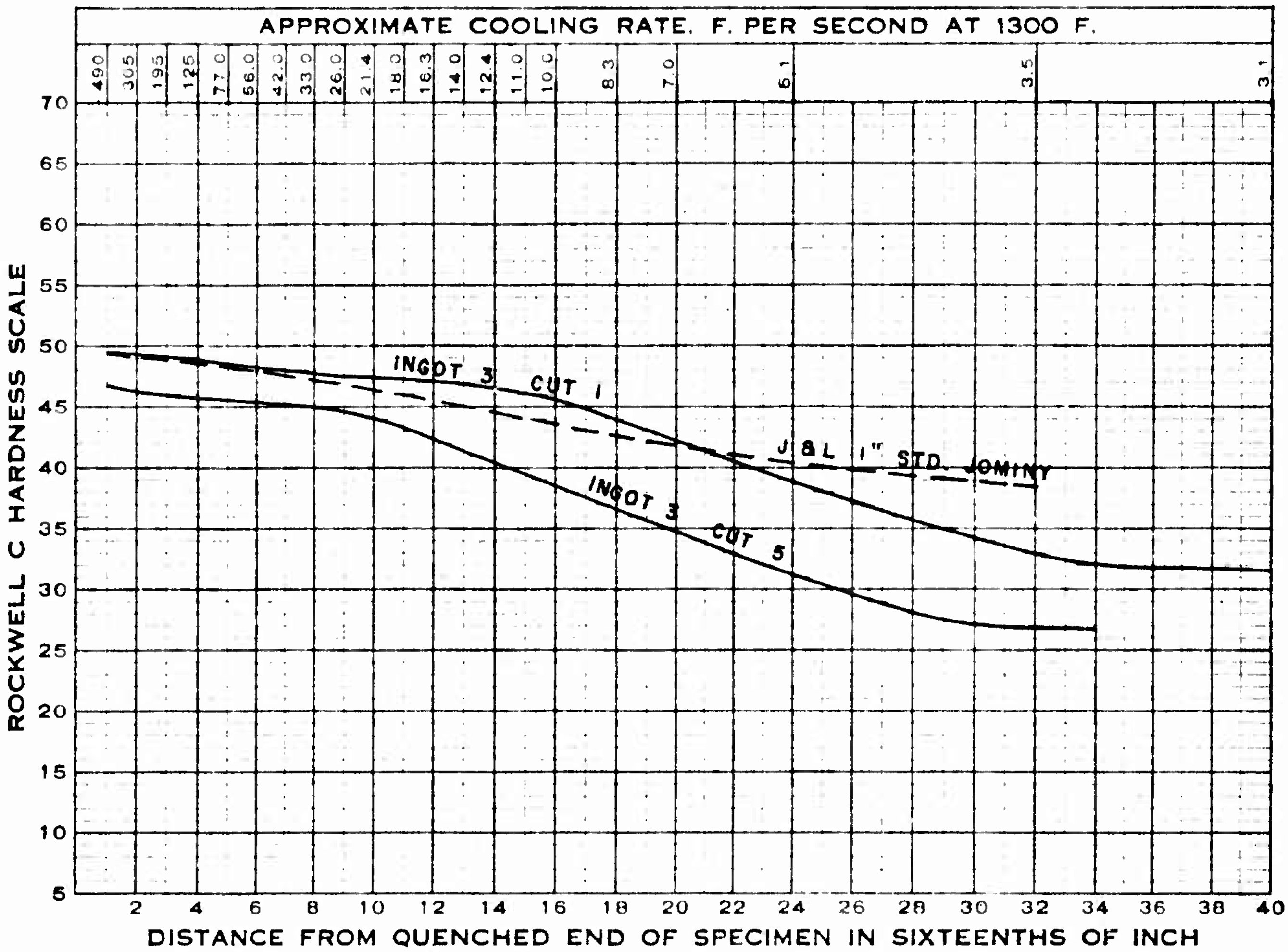
MR 207A

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 48 T)

DATE 5-17-54
LABORATORY ACF
TYPE SPECIMEN 1/2" D (SAE)
TEST NO

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F	QUENCH TEMP. °F
ARMOR	JL 0724		.27	1.59	.012	.024	.15	.03	.02	.46		1650	1625
	ING. 3 CUT 1												
ARMOR	JL 0724		.25	1.58	.013	.019	.18	.03	.03	.44		1650	1625
	ING. 3 CUT 5												

REMARKS:



AMERICAN SOCIETY FOR TESTING MATERIALS

Figure 2
END QUENCH HARDENABILITY DATA
HEAT JL 0724

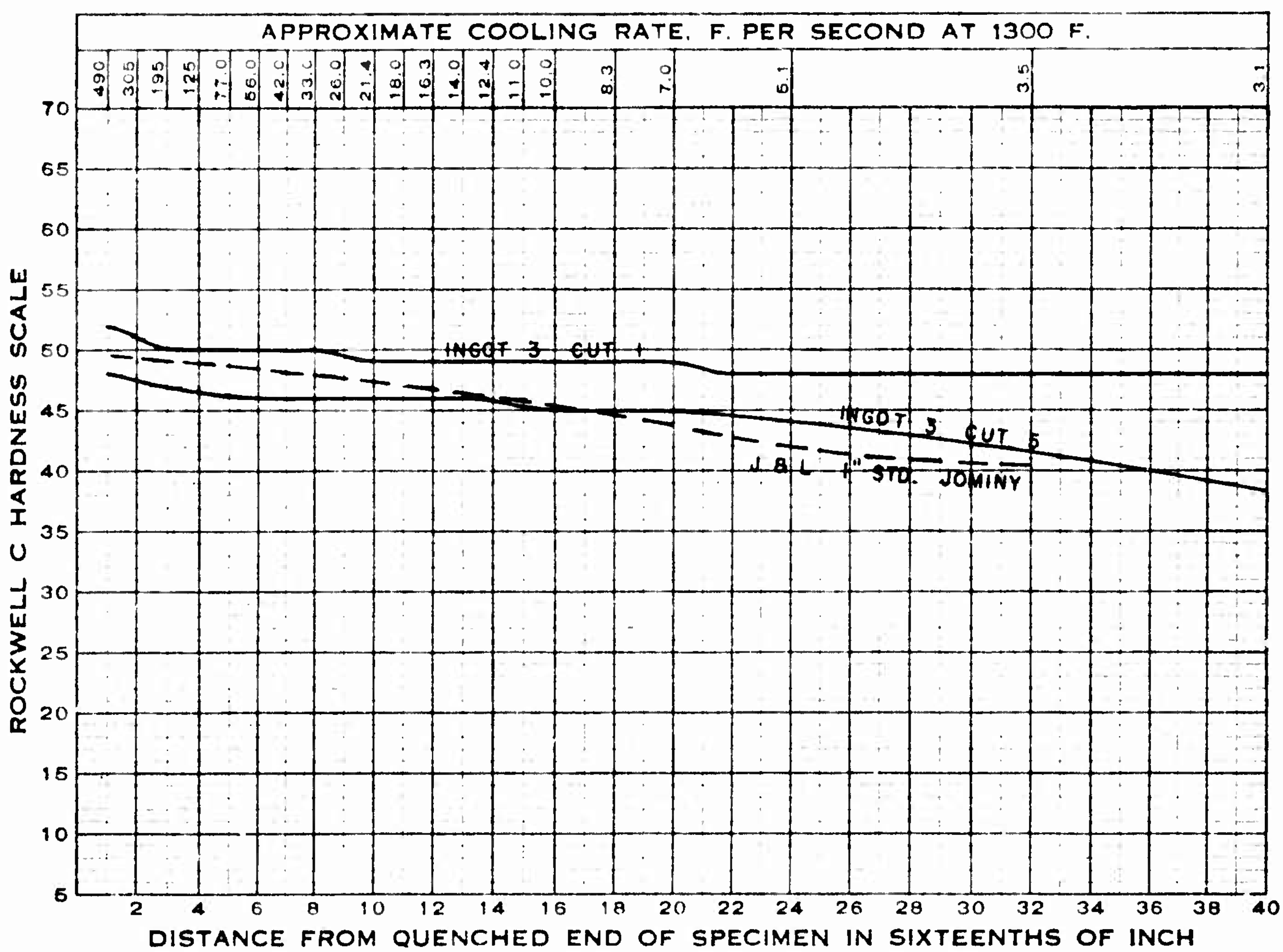
MR 207A

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 48 T)

DATE 5-17-54
LABORATORY ACF
TYPE SPECIMEN 1/2" D (SAE)
TEST NO

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM TEMP. F	QUENCH TEMP. F.
ARMOR	JL 0823		.30	1.71	.020	.024	.17	.01	.03	.40		1650	1625
	ING. 3 CUT 1												
ARMOR	JL 0823		.23	1.66	.017	.018	.18	.01	.02	.42		1650	1625
	ING. 3 CUT 5												

REMARKS:



AMERICAN SOCIETY FOR TESTING MATERIALS
1916 RACE ST. PHILADELPHIA 3, PA.

Figure 3
END QUENCH HARDENABILITY DATA
HEAT JL 0823

MR 207A

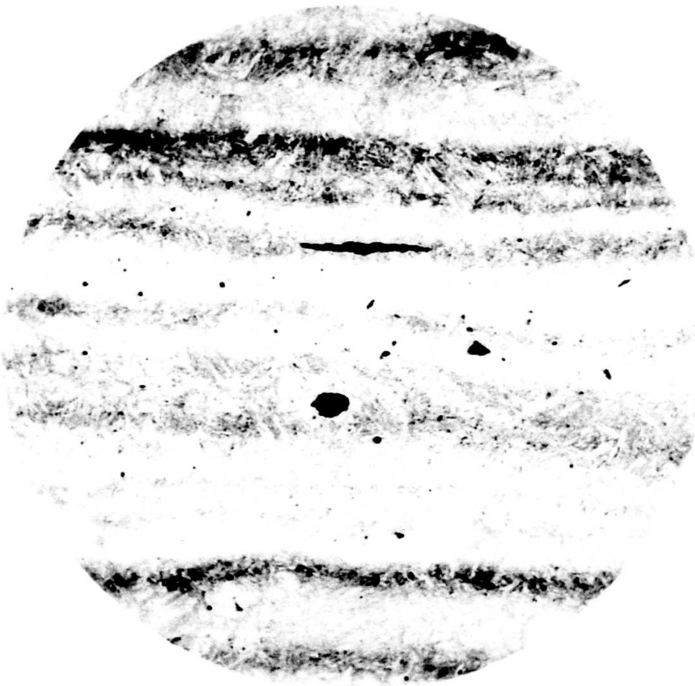


Figure 4

Boiling sodium picrate etch X500
Typical sulfide inclusion in Heat 0681, Cut 5.

M-10-307-FF
MR 207A

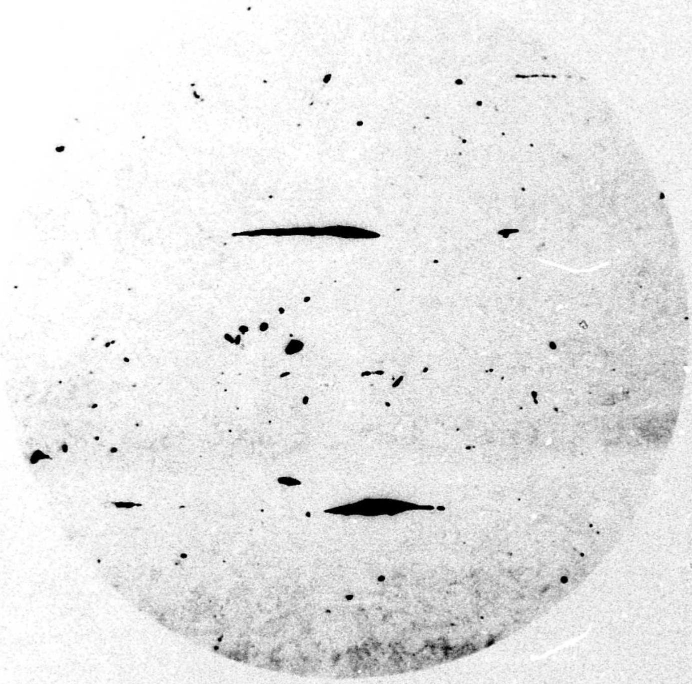


Figure 5

Boiling sodium picrate etch X500
Typical sulfide inclusion in Heat 0724, Cut 5.

M-10-307-GG
MR 207A

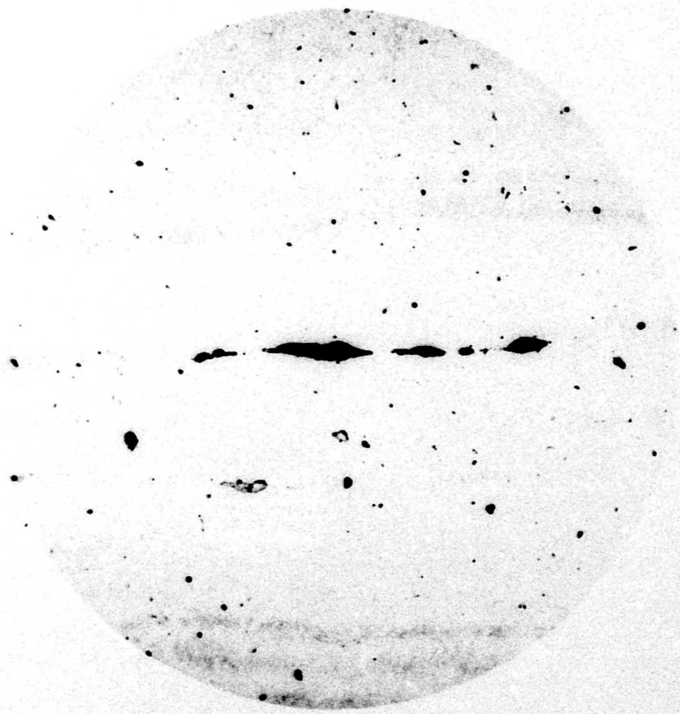
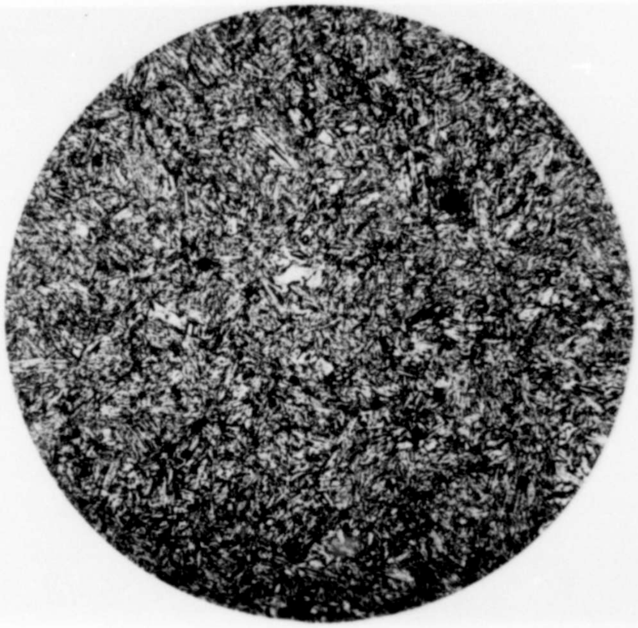


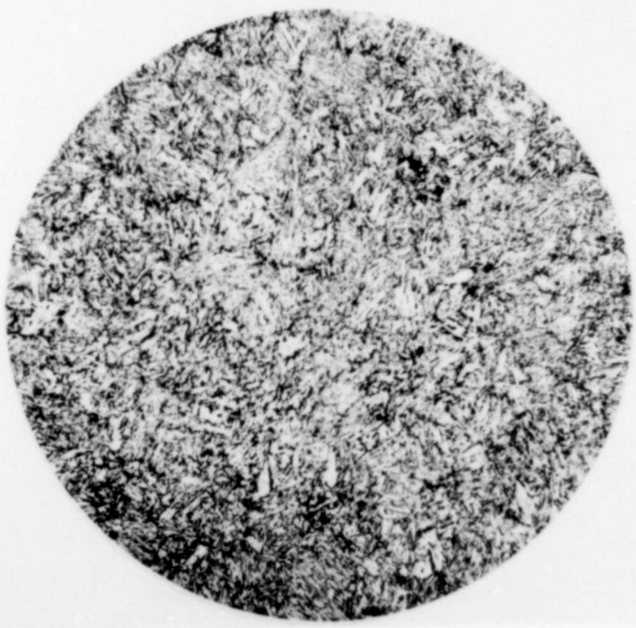
Figure 6

Boiling sodium picrate etch X500
Typical sulfide inclusion in Heat 0823, Cut 5.

M-10-307-HH
MR 207A



Ingot 1, Cut 1

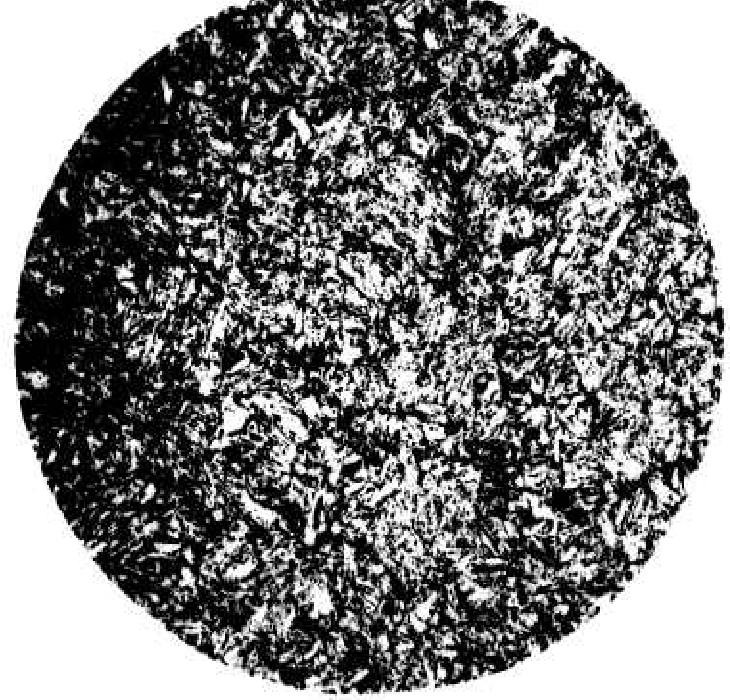


Ingot 1, Cut 5

Figure 7

Picral etch X500
Microstructure of Heat 0681.

M-10-307-W
MR 207A



Ingot 3, Cut 1

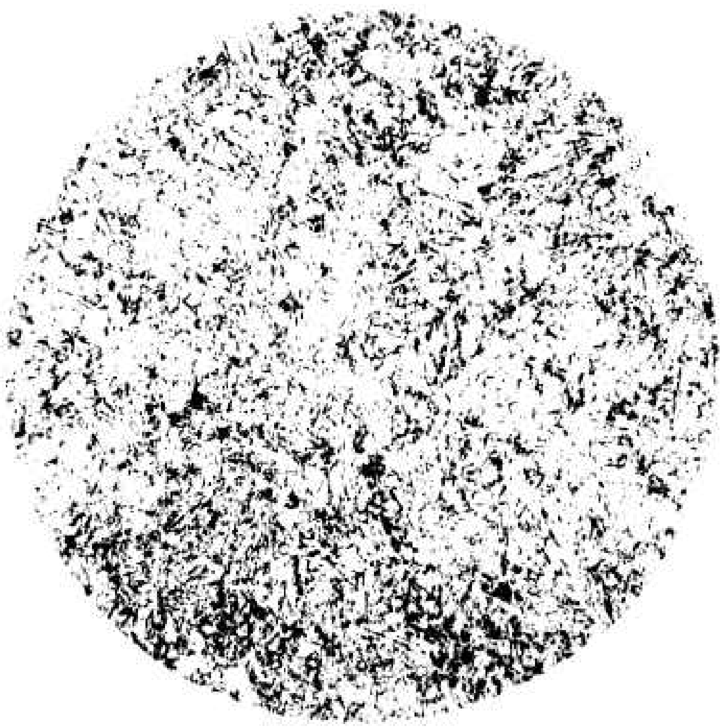
Ingot 3, Cut 5

Figure 8

Picral etch X500
Microstructure of Heat 0724.

M-10-307-AA
MR 207A

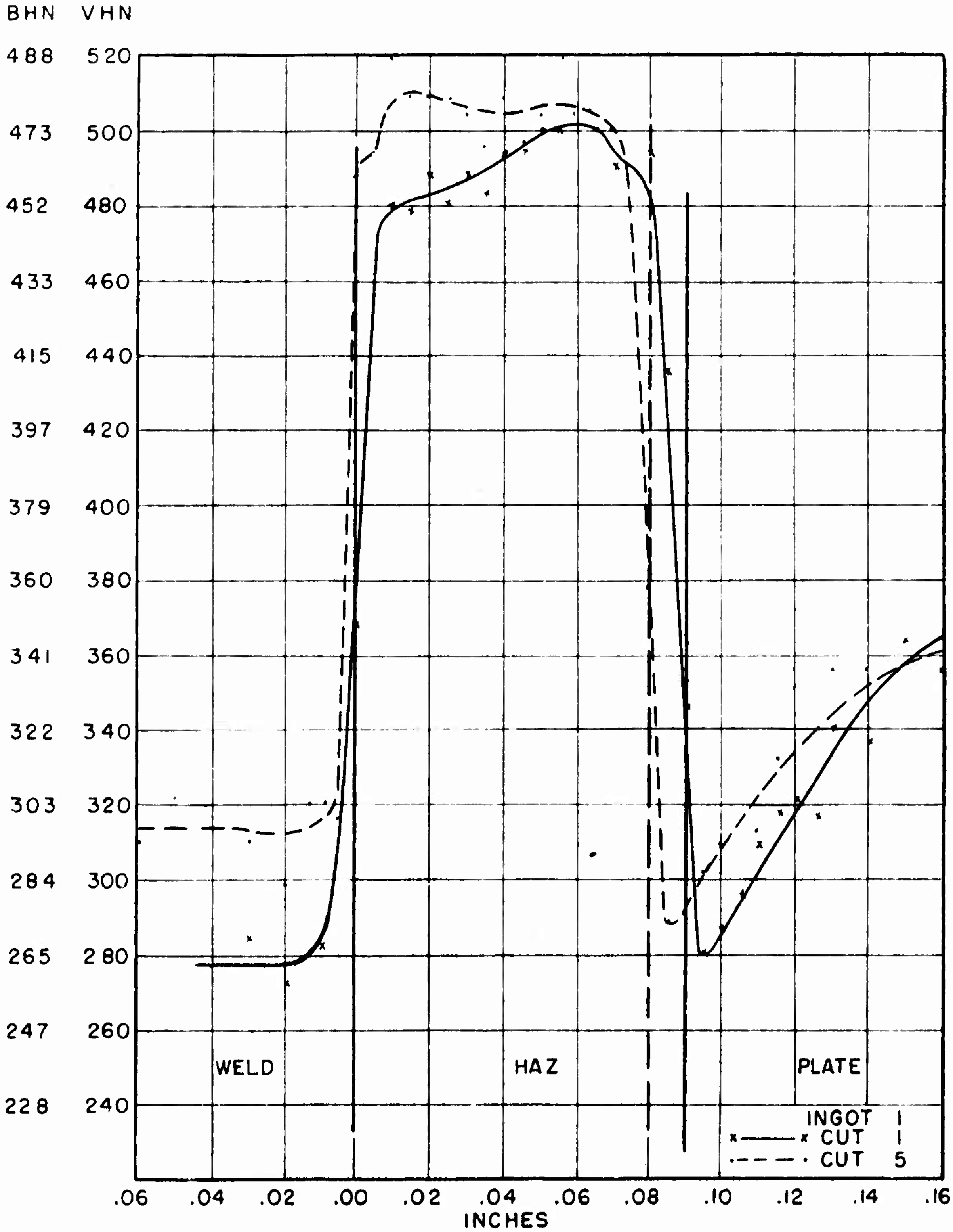
Ingot 3, Cut 1



Ingot 3, Cut 5

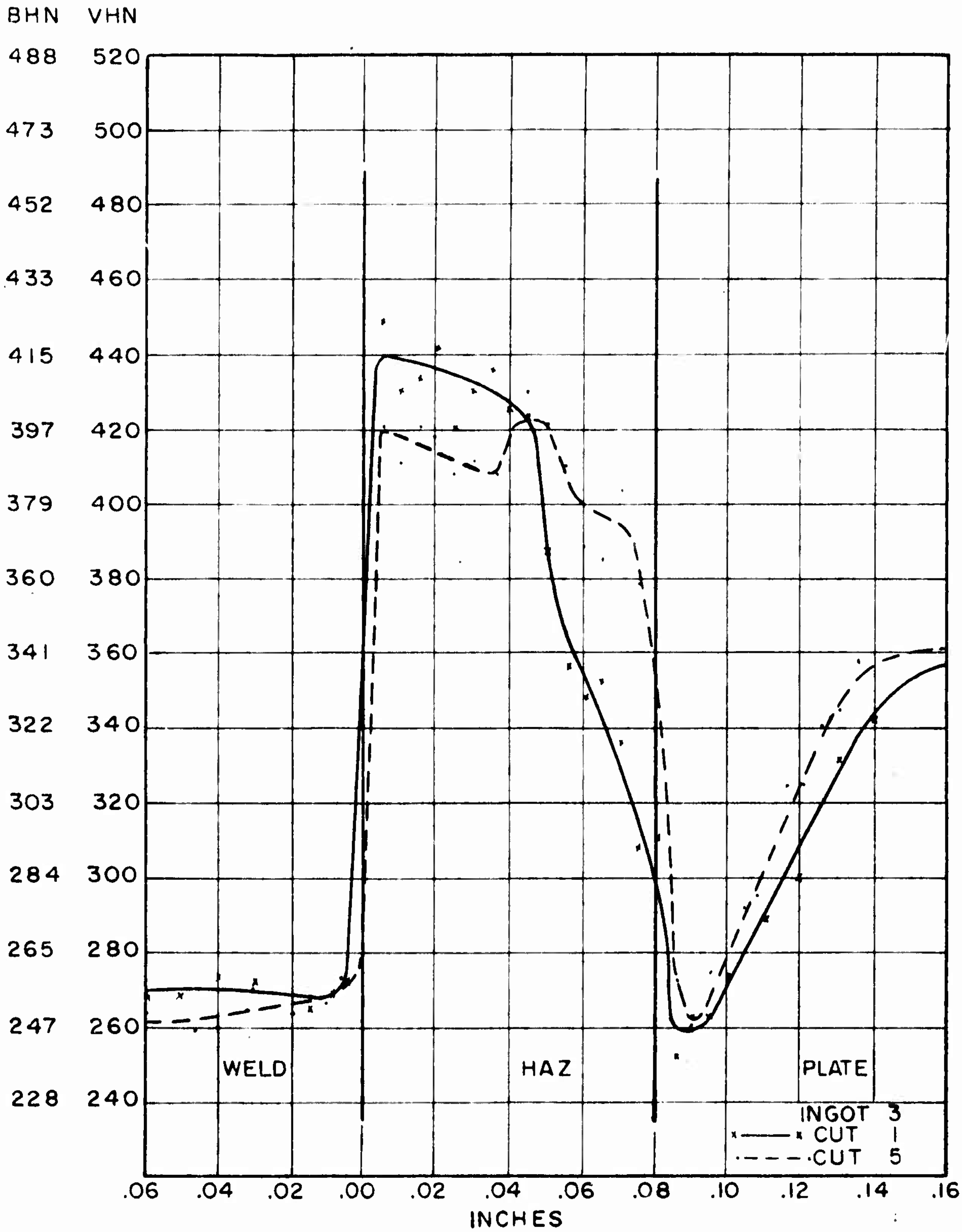
Figure 9

Picral etch X500
Microstructure of Heat 0823.



MICROHARDNESS SURVEY
HEAT JL 0681

ACF INDUSTRIES, INCORPORATED
RESEARCH AND DEVELOPMENT DEPARTMENT



MICROHARDNESS SURVEY
HEAT JL 0724

ACF INDUSTRIES, INCORPORATED
RESEARCH AND DEVELOPMENT DEPARTMENT

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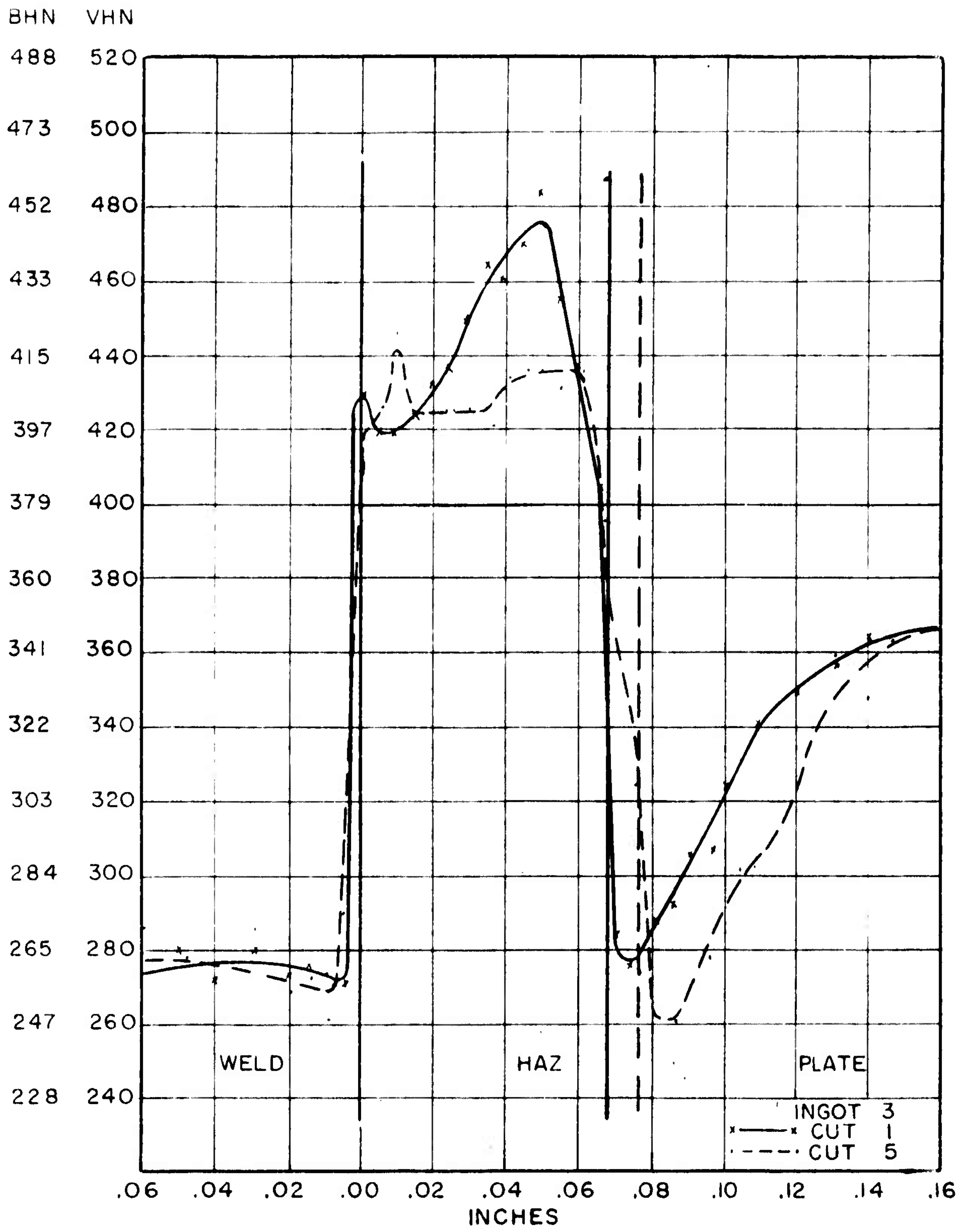
Figure 11



MICROHARDNESS SURVEY

HEAT JL 0823

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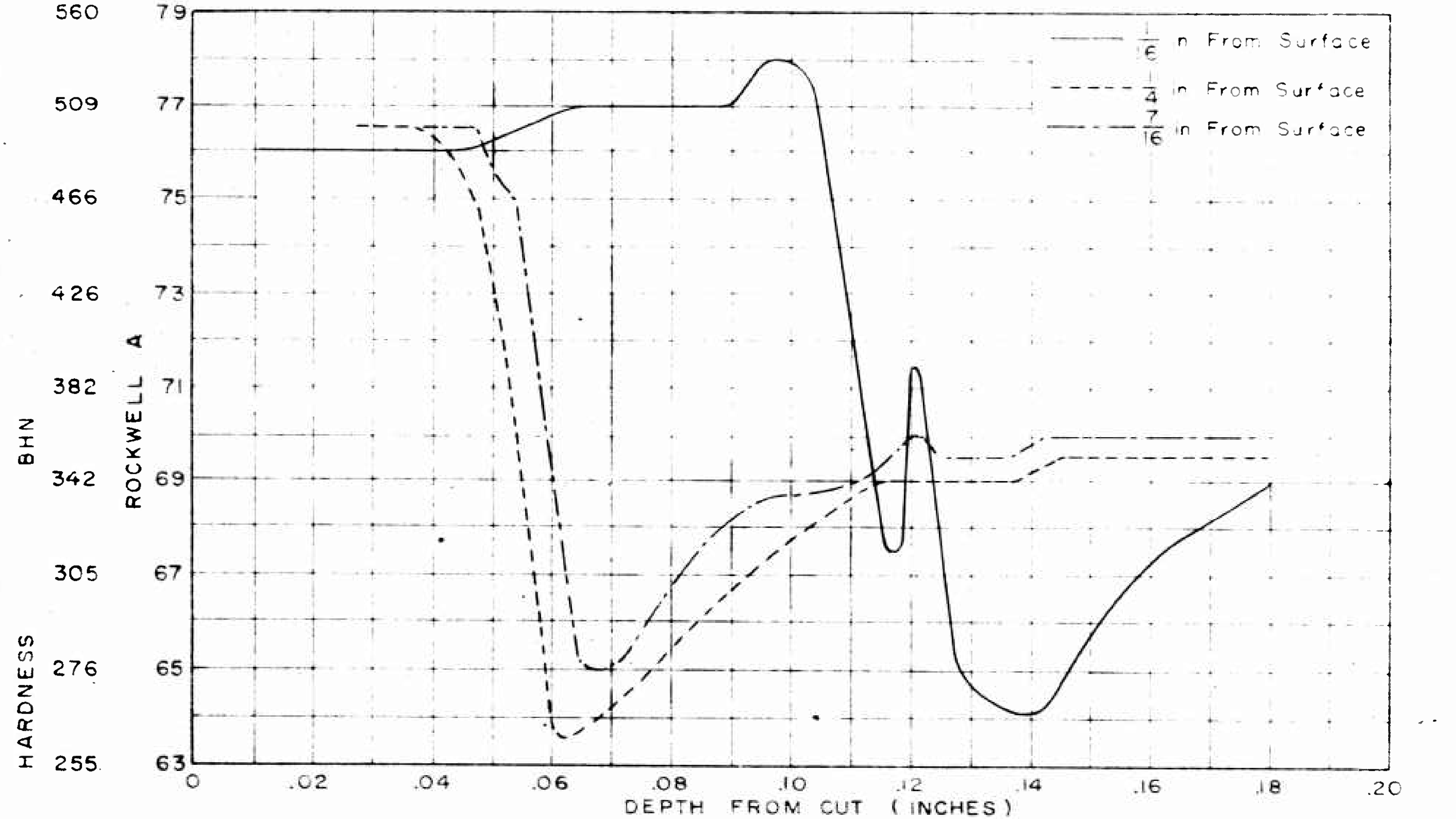
Figure 12



GAS CUT EDGE HARDNESS

SPECIMEN A1
HEAT JL 0681
INGOT 1 CUT 1

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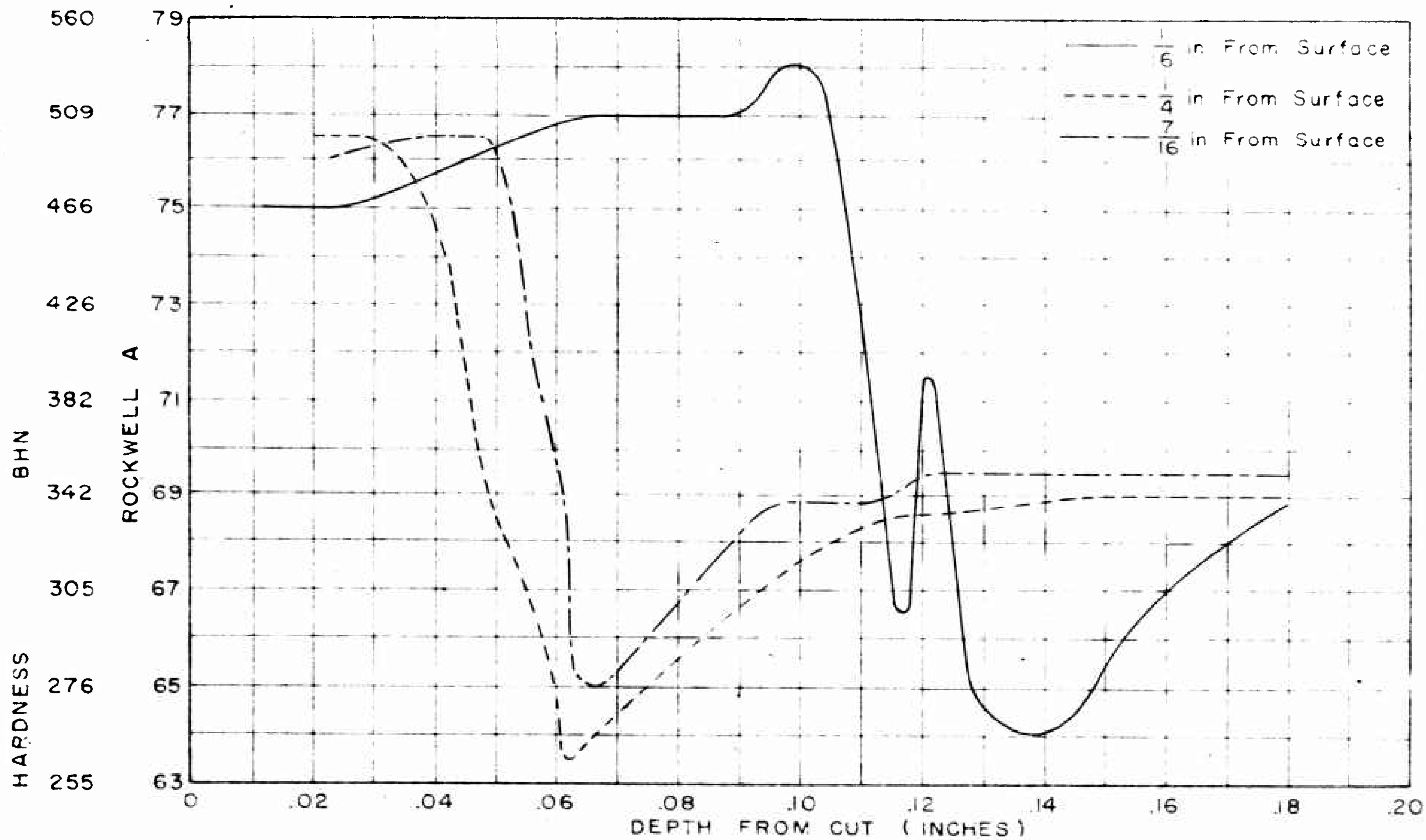
Figure 13



GAS CUT EDGE HARDNESS

SPECIMEN A122
HEAT JL 0681
INGOT I CUT 5

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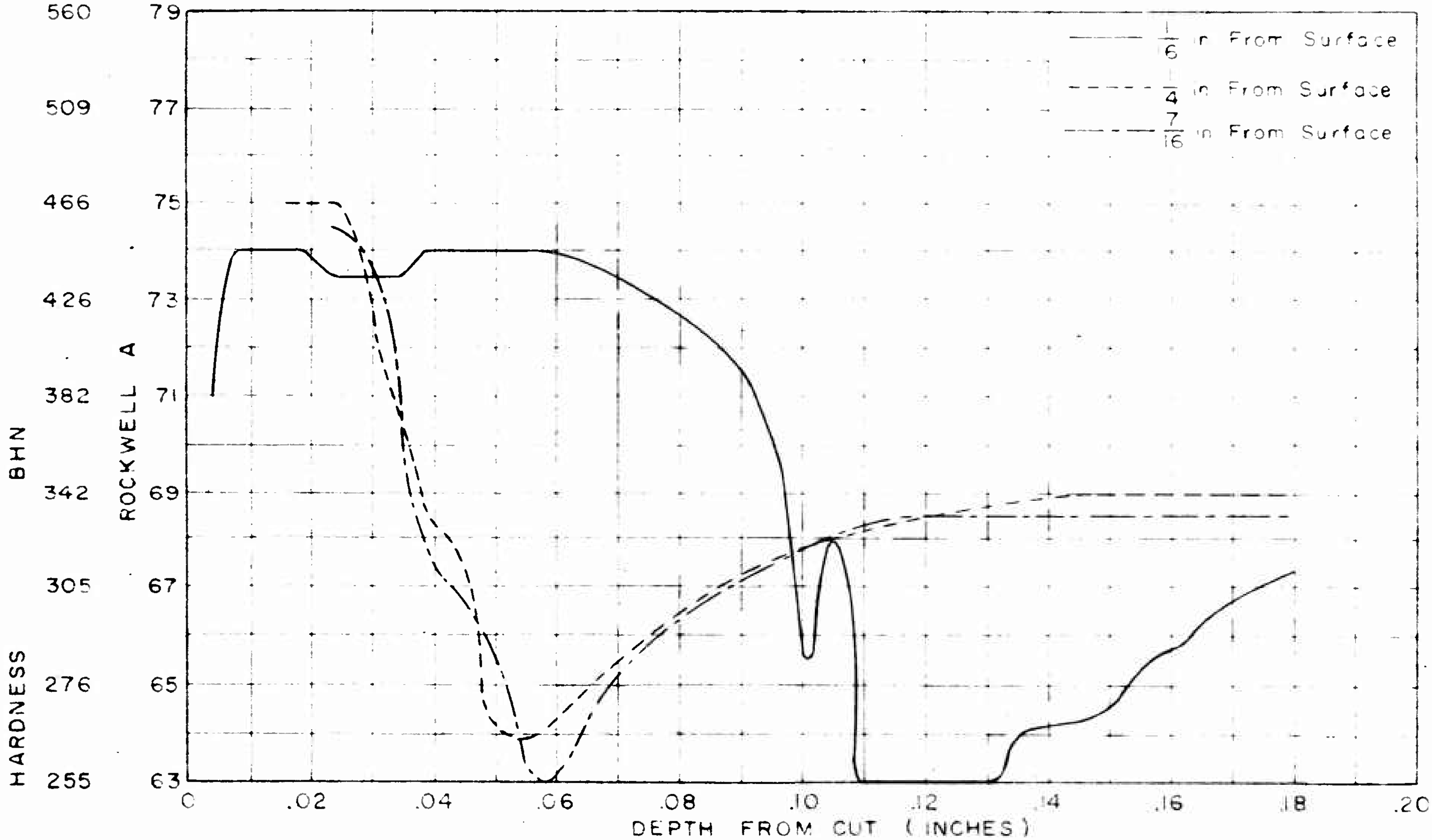
Figure 14



GAS CUT EDGE HARDNESS

SPECIMEN B1
HEAT JL 0724
INGOT 3 CUT 1

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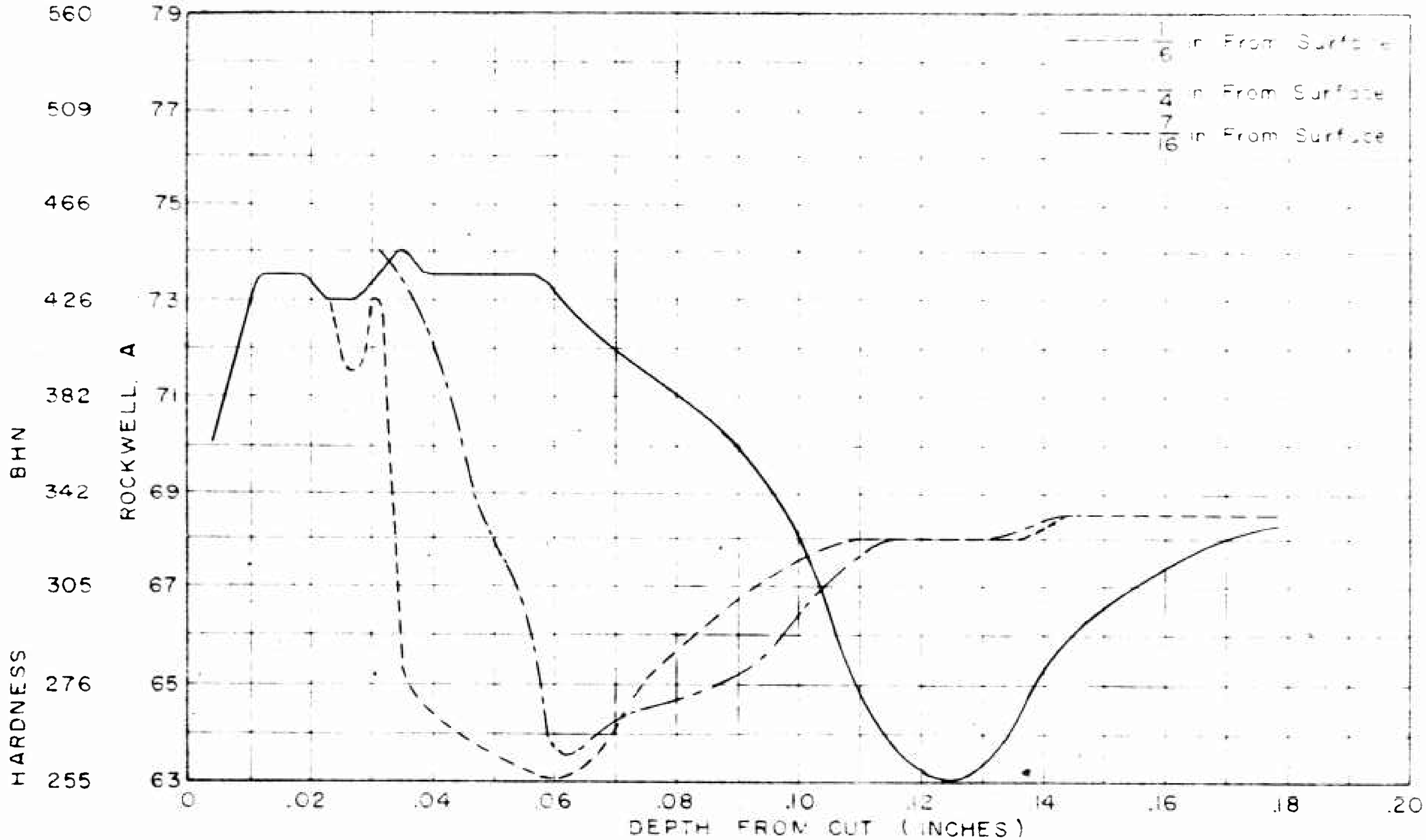
Figure 15



GAS CUT EDGE HARDNESS

SPECIMEN B123
HEAT JL 0724
INGOT 3 CUT 5

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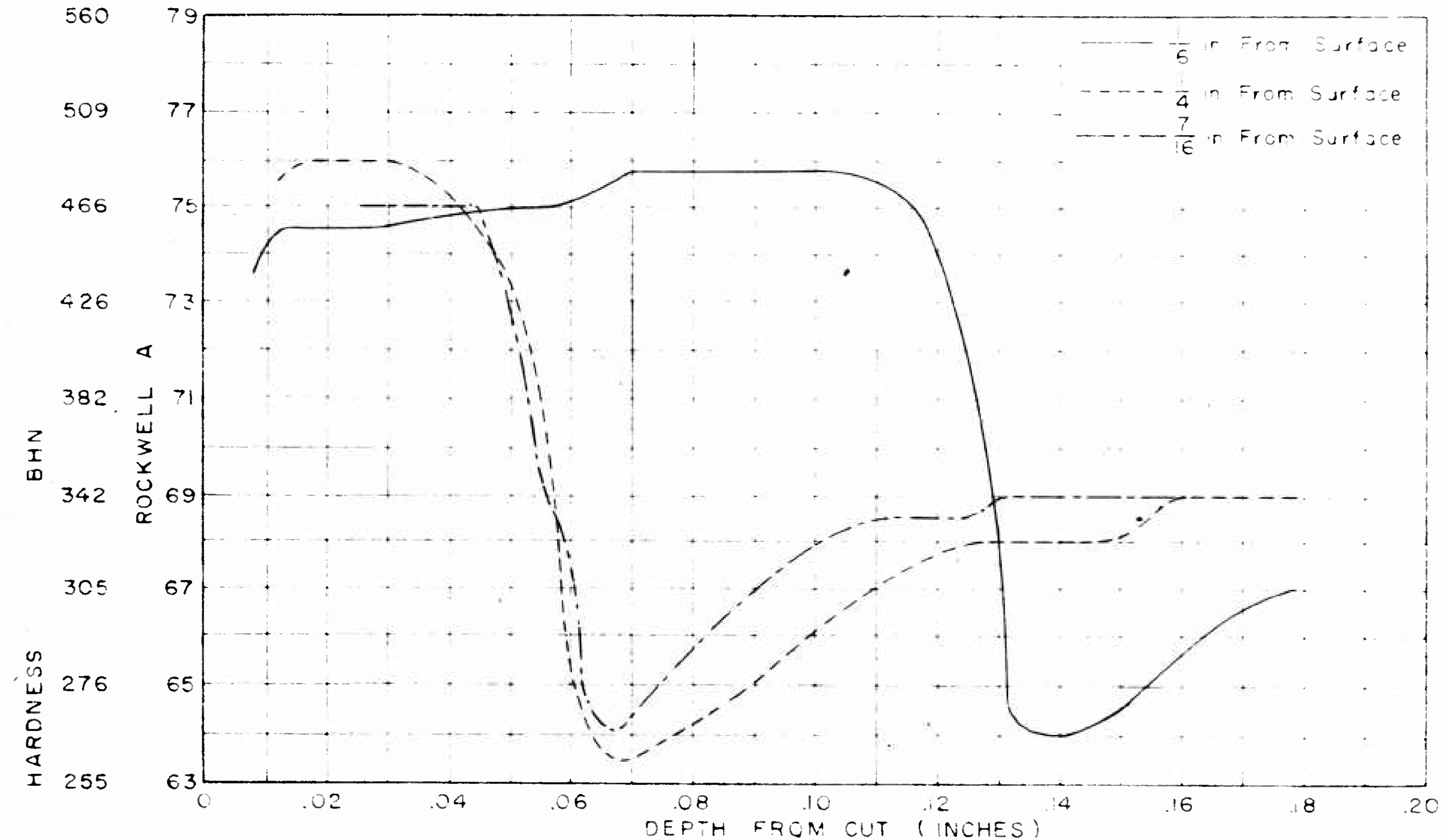
Figure 16



GAS CUT EDGE HARDNESS

SPECIMEN C1
HEAT JL 0823
INGOT 3 CUT 1

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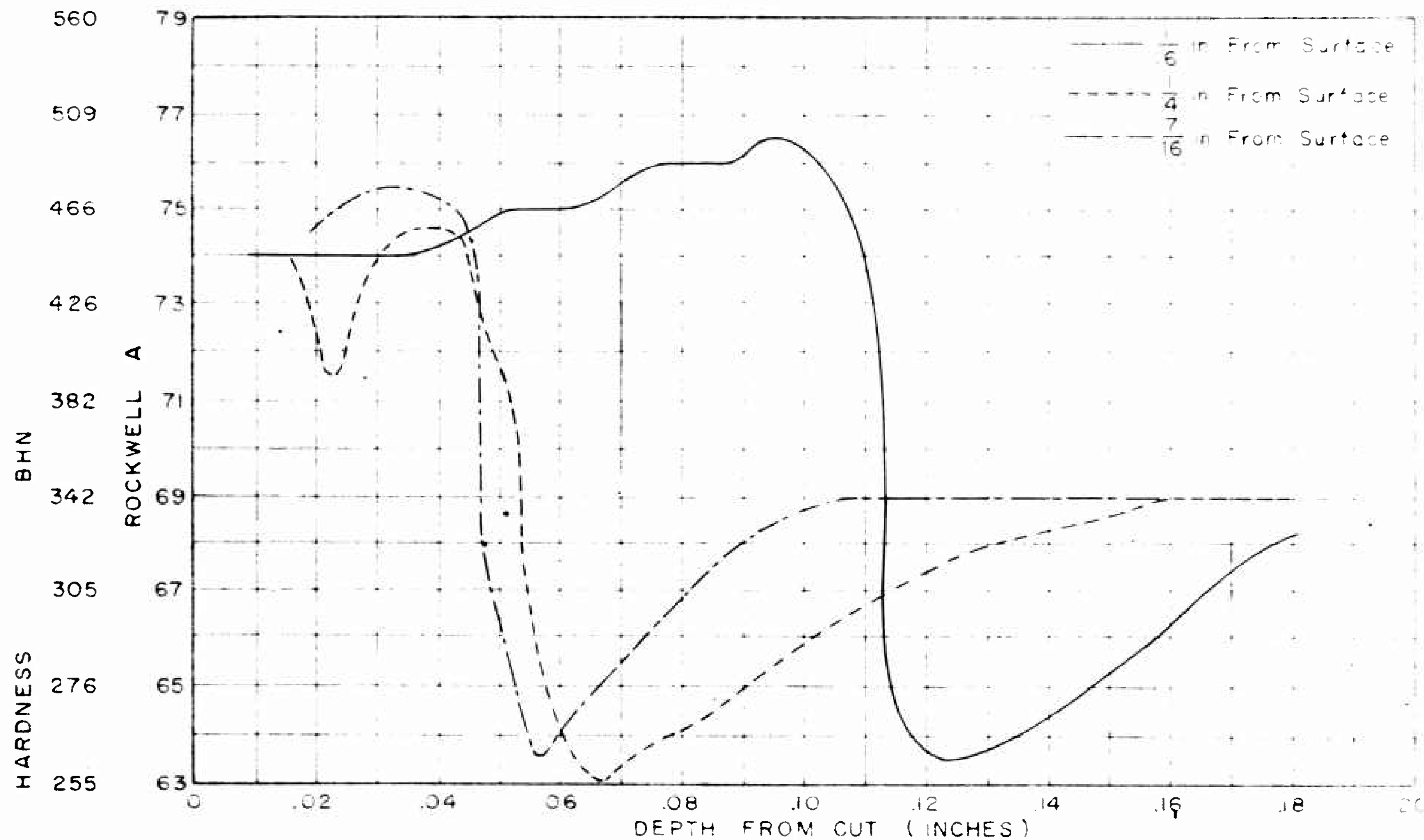
Figure 17



GAS CUT EDGE HARDNESS

SPECIMEN C 123
HEAT JL 0823
INGOT 3 CUT 5

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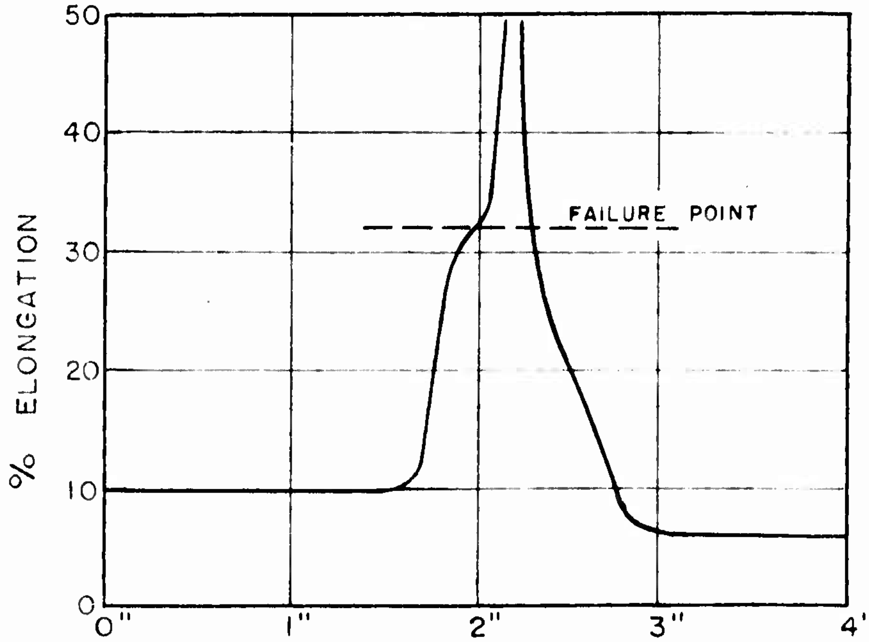
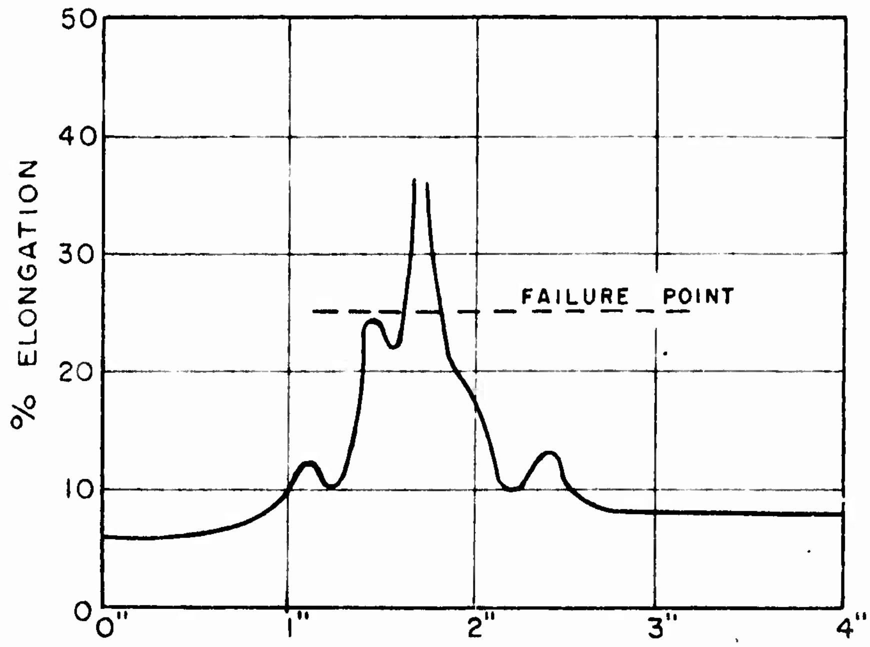
Figure 18



SPECIMEN A35
HEAT JL 0681
INGOT I CUT I



SPECIMEN A116
HEAT JL 0681
INGOT I CUT 5

BEND TESTS

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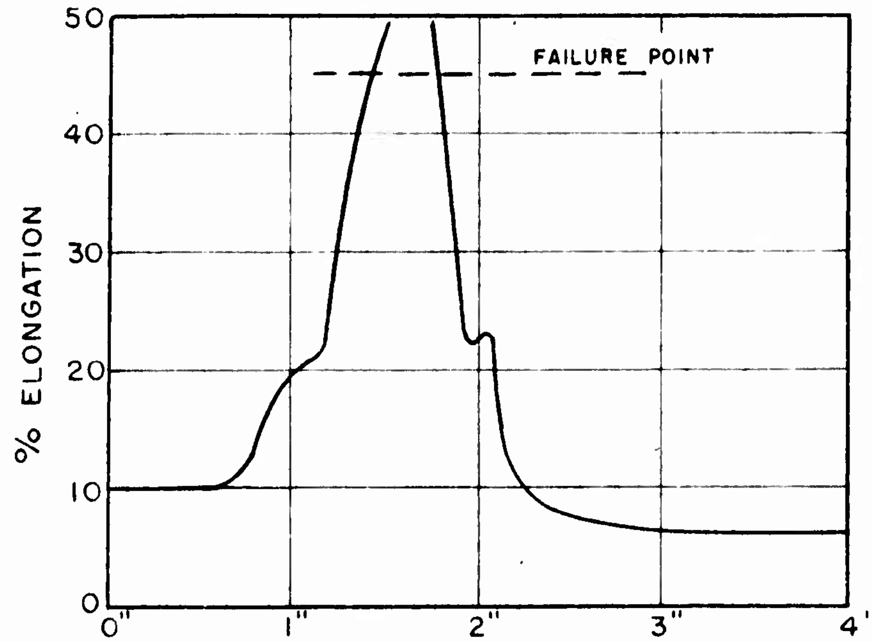
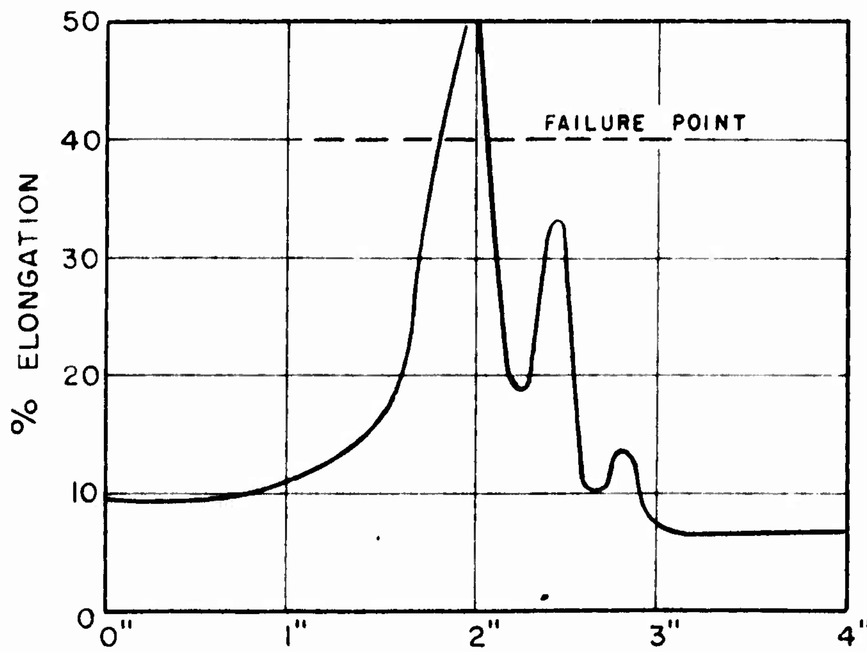
Figure 19



SPECIMEN B18
HEAT JL 0724
INGOT 3 CUT 1



SPECIMEN B121
HEAT JL 0724
INGOT 3 CUT 5

BEND TESTS

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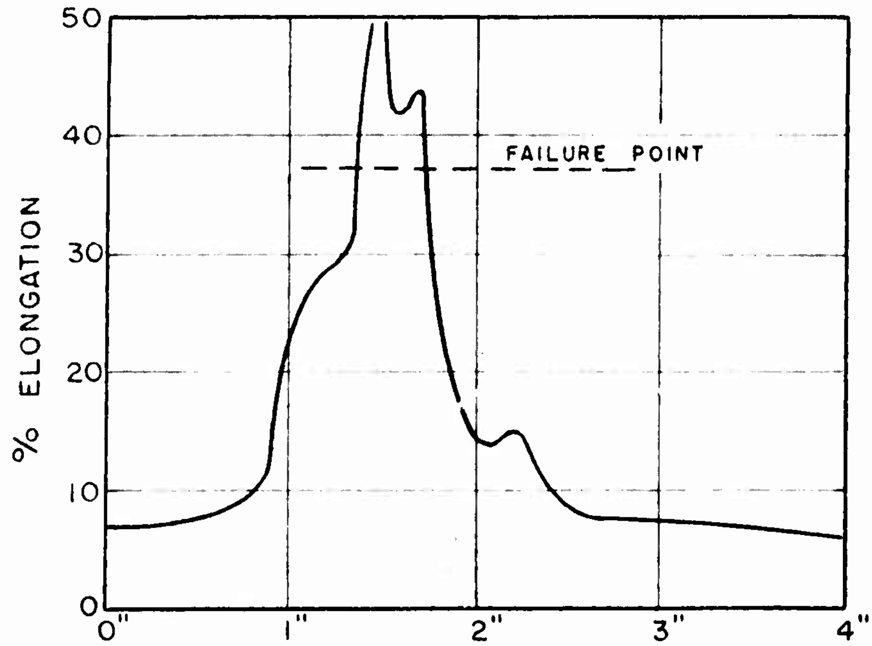
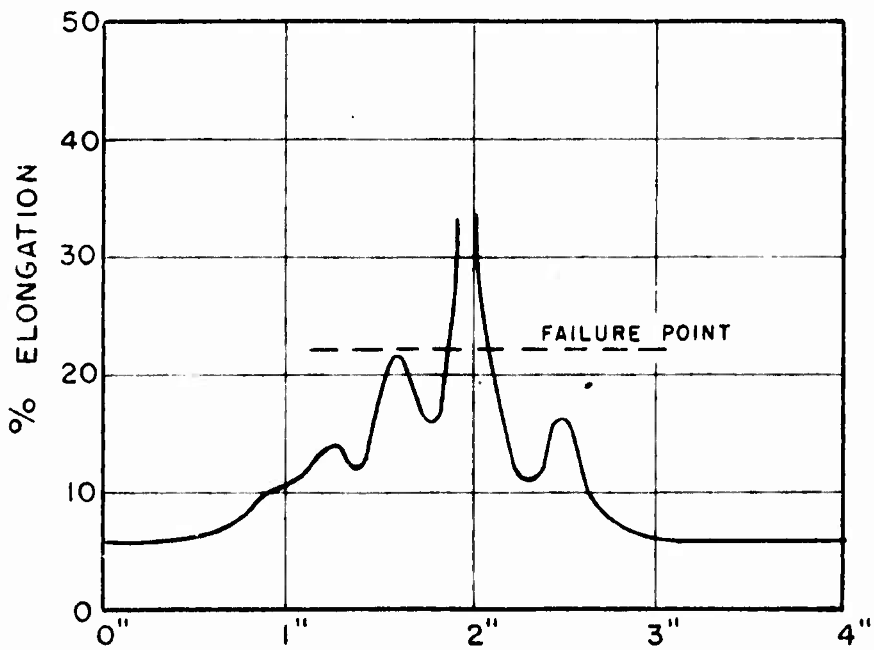
Figure 20



SPECIMEN C36
HEAT JL 0823
INGOT 3 CUT 1



SPECIMEN C118
HEAT JL 0823
INGOT 3 CUT 5

BEND TESTS

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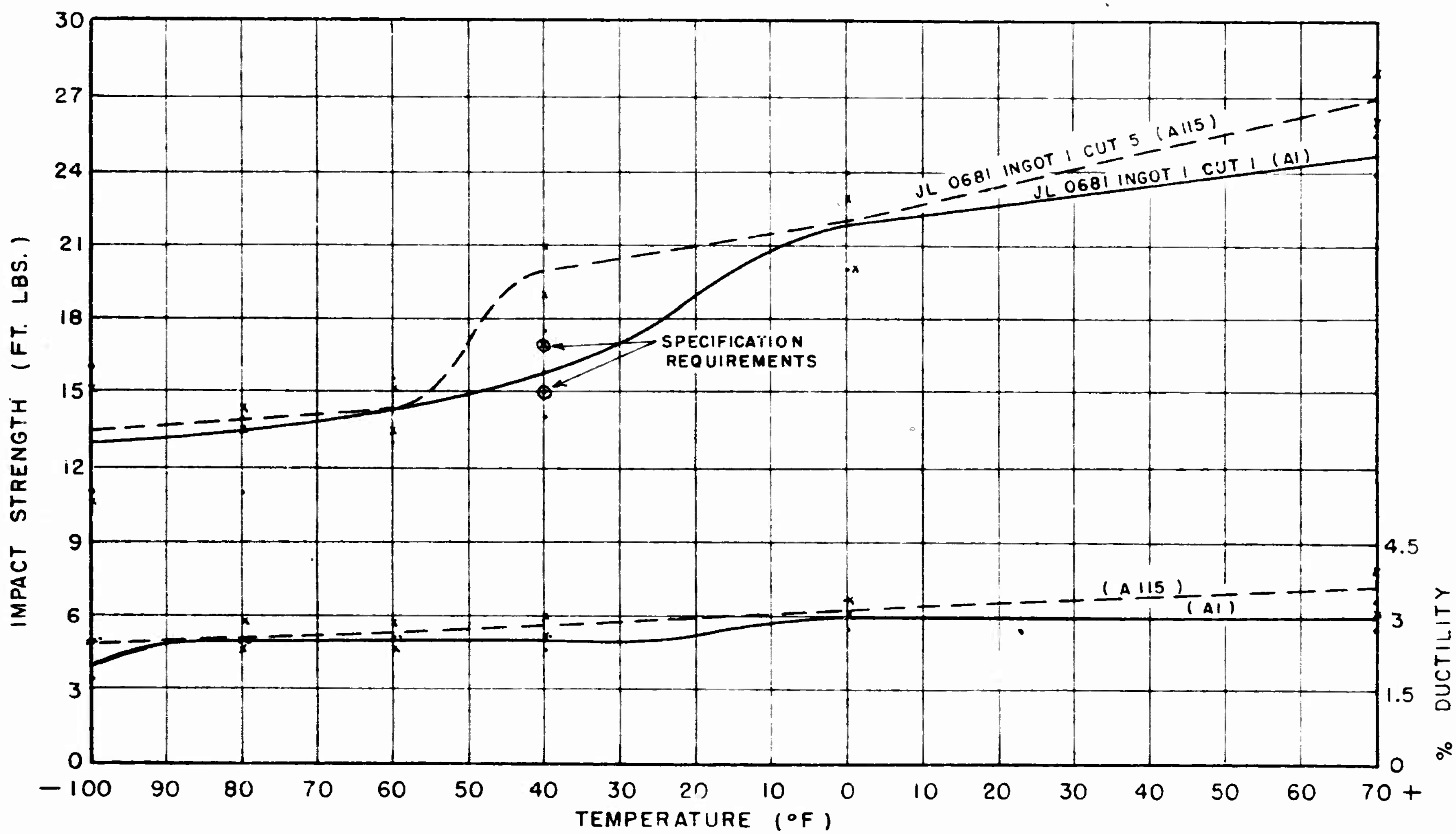
Figure 21



NOTCH IMPACT STRENGTH
AND SPECIMEN DUCTILITY
CHARPY V NOTCH TEST

MR 207A

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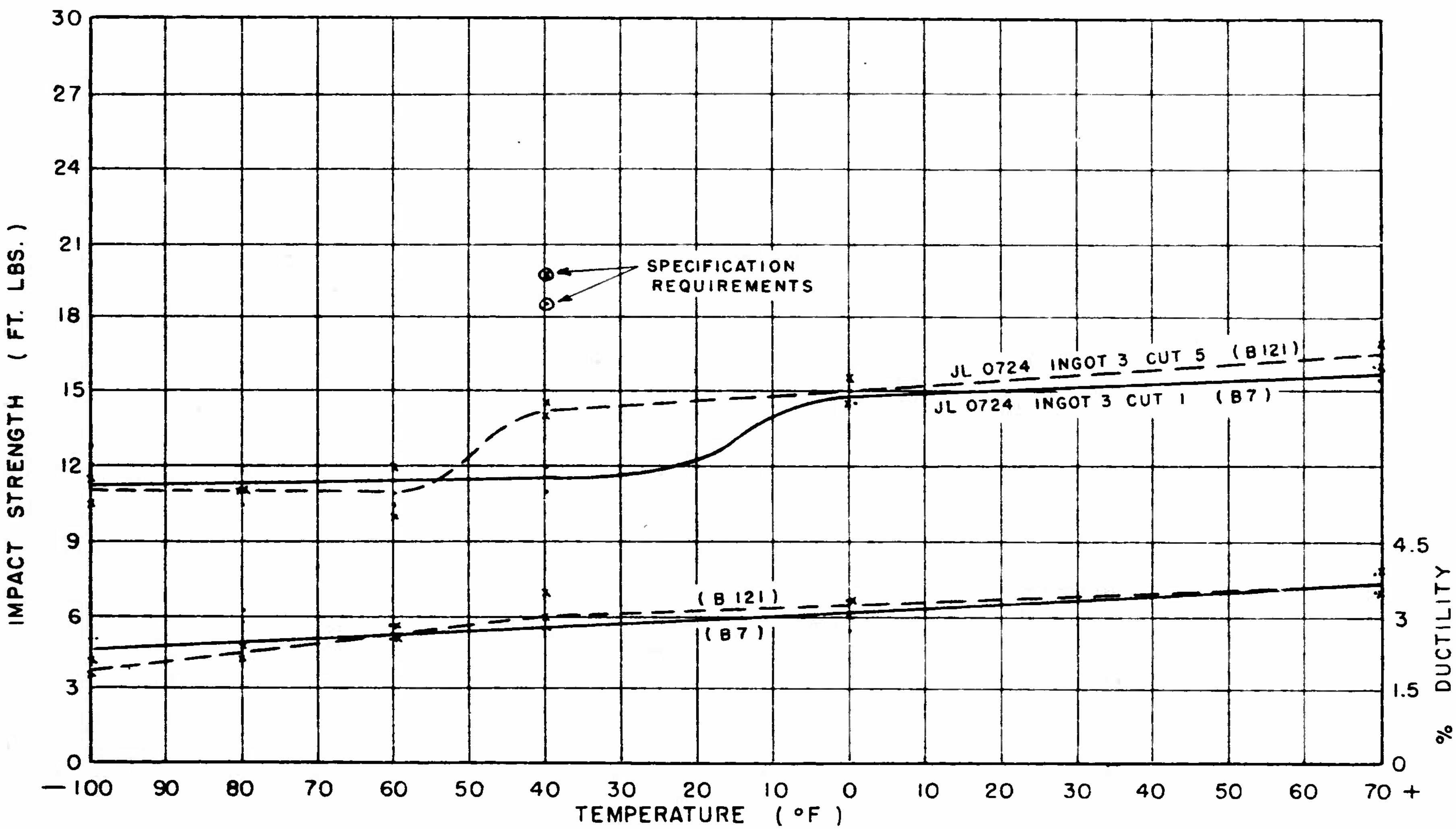
RESEARCH AND DEVELOPMENT DEPARTMENT

Figure 22



NOTCH IMPACT STRENGTH
AND SPECIMEN DUCTILITY
CHARPY V NOTCH TEST

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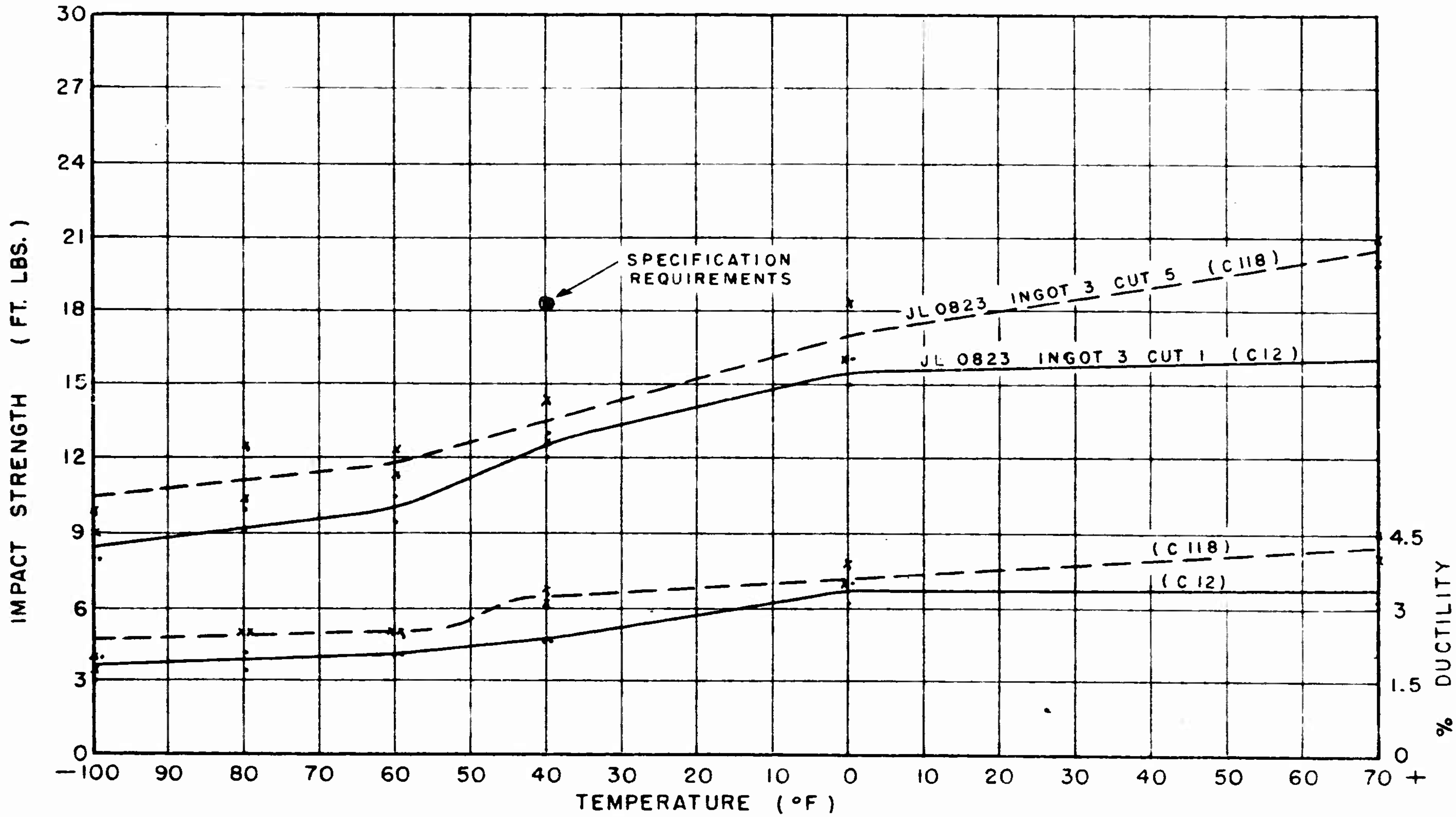
Figure 23

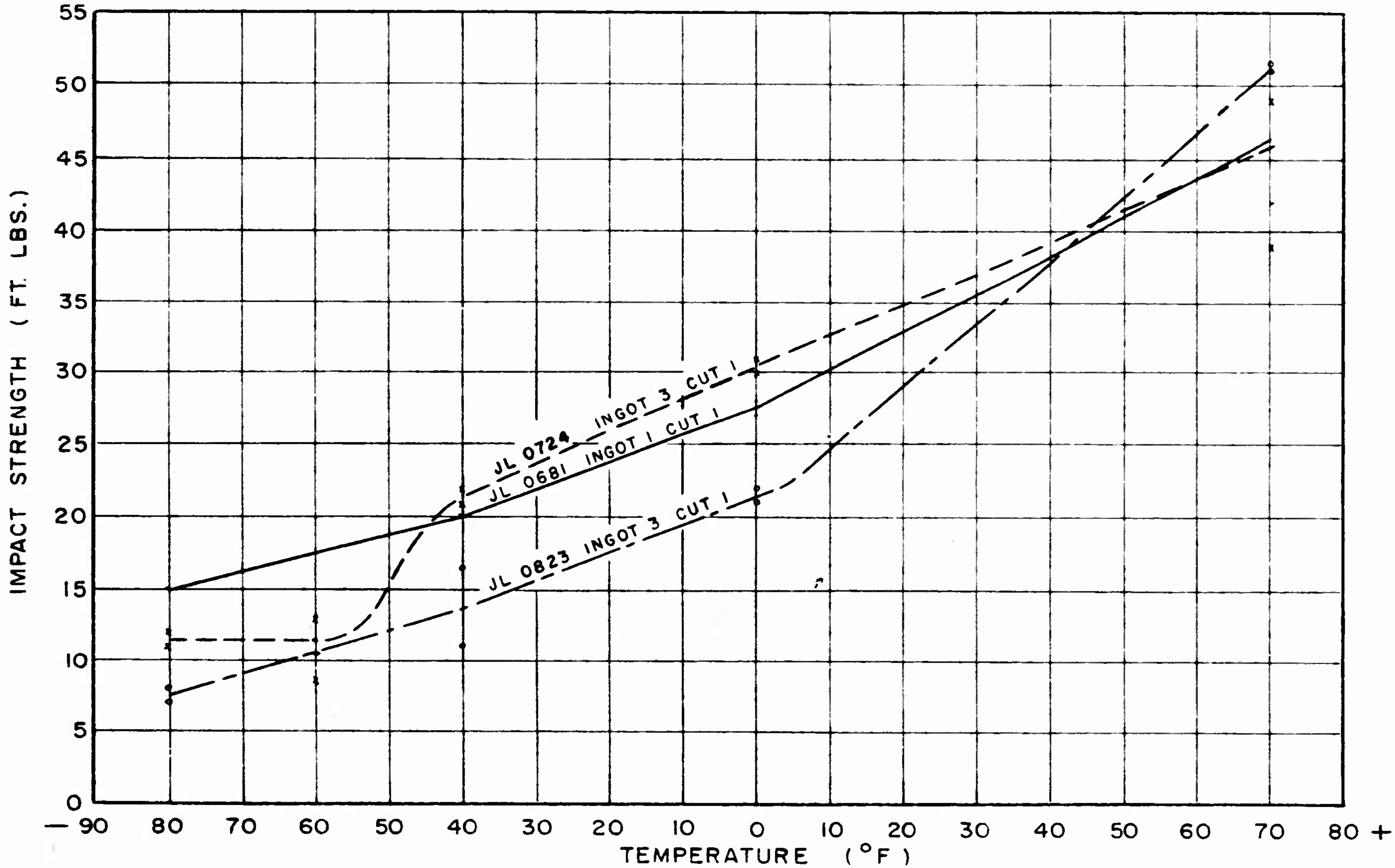


NOTCH IMPACT STRENGTH
AND SPECIMEN DUCTILITY
CHARPY V NOTCH TEST

ACF INDUSTRIES, INCORPORATED
RESEARCH AND DEVELOPMENT DEPARTMENT

MR 207A

Figure 24



WELD DEPOSIT
NOTCH IMPACT STRENGTH
CHARPY V NOTCH TEST

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Figure 25

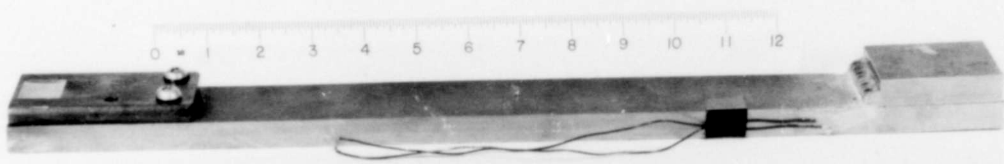


Figure 26

Typical test specimen with strain gage
and wear plate in place.

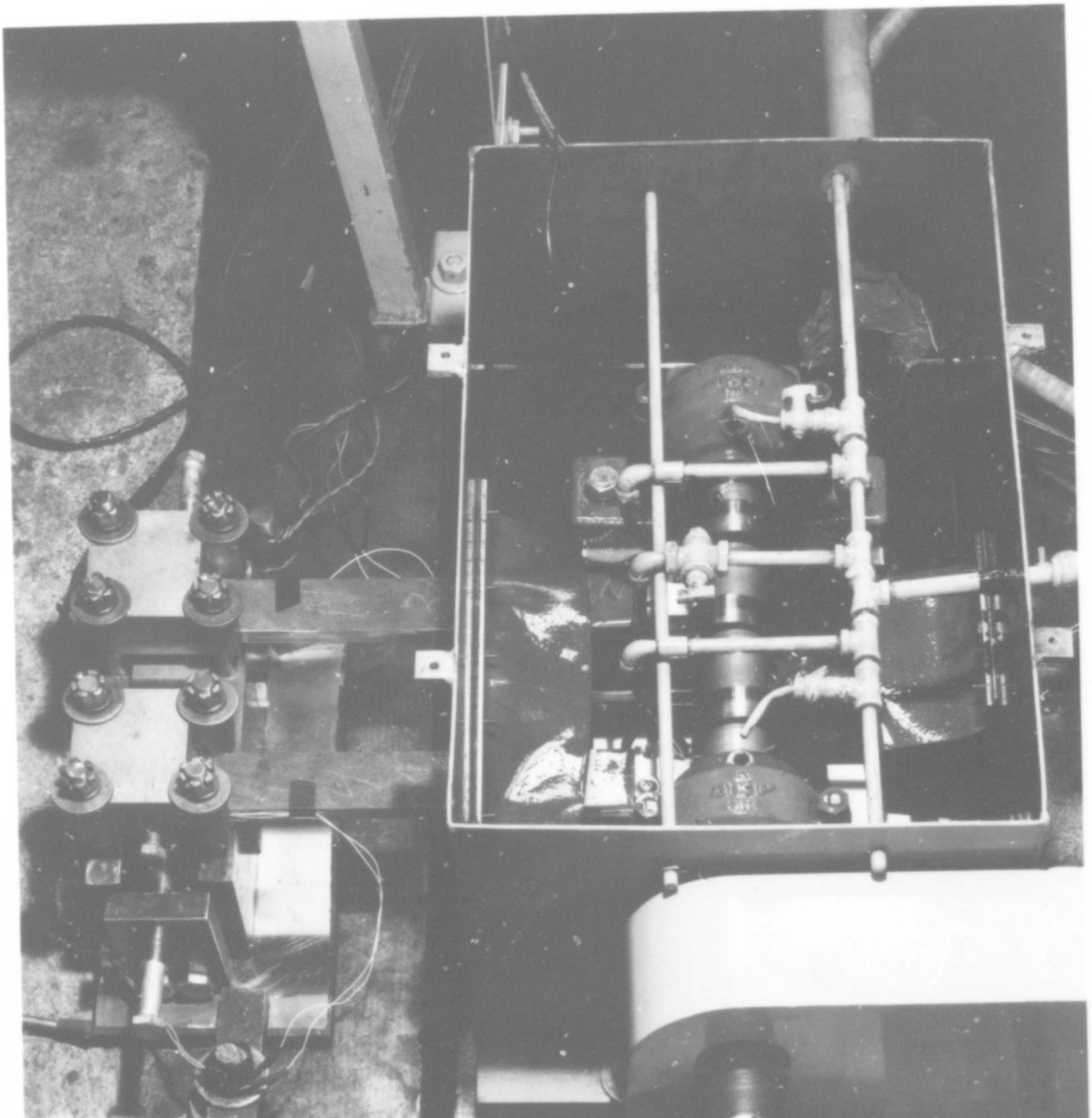


Figure 27

View of apparatus with specimens in place.

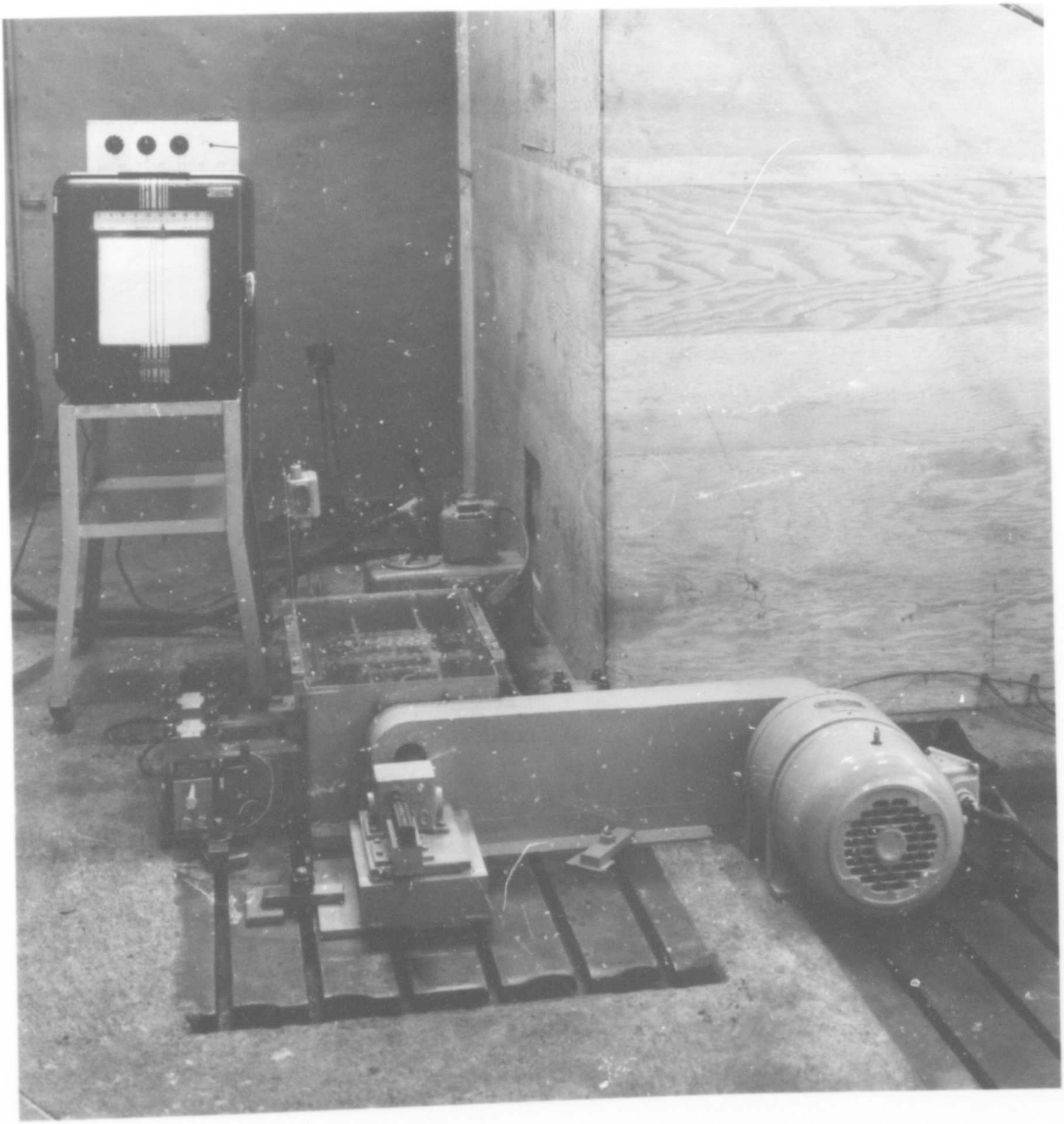
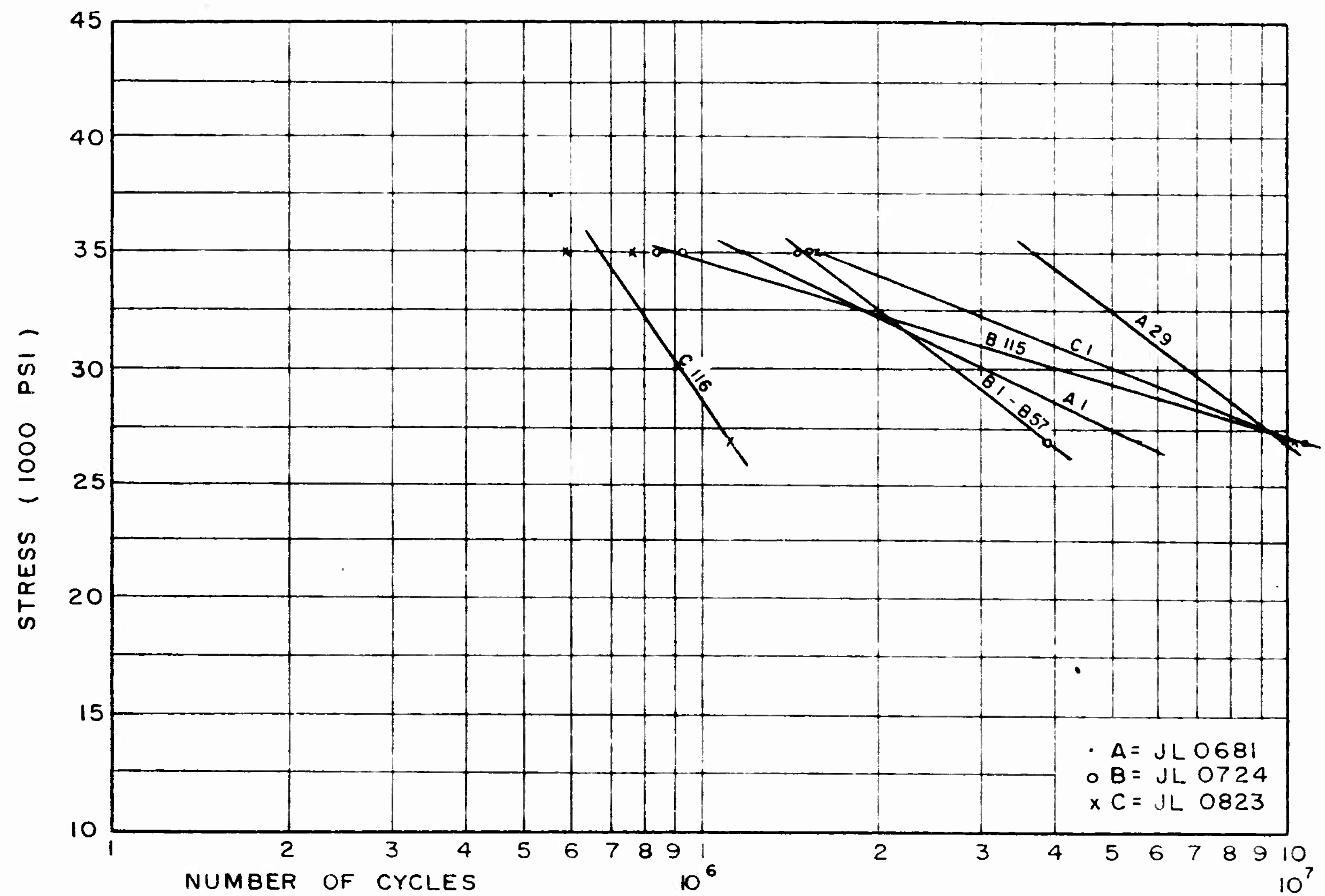


Figure 28

Over-all view of test setup.

M-10-239-A
MR 207A



FATIGUE STRENGTH

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MR 207A

Figure 29

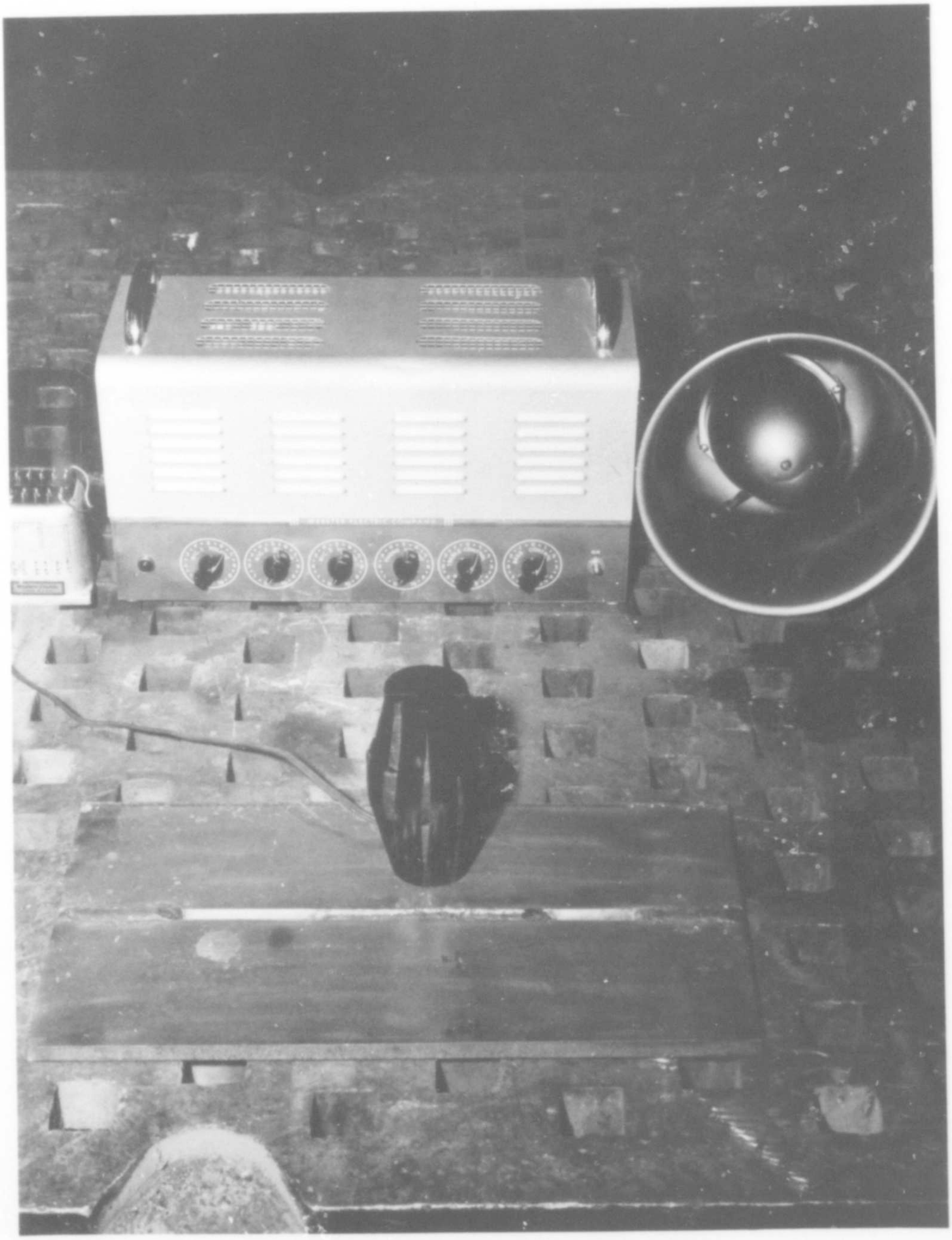
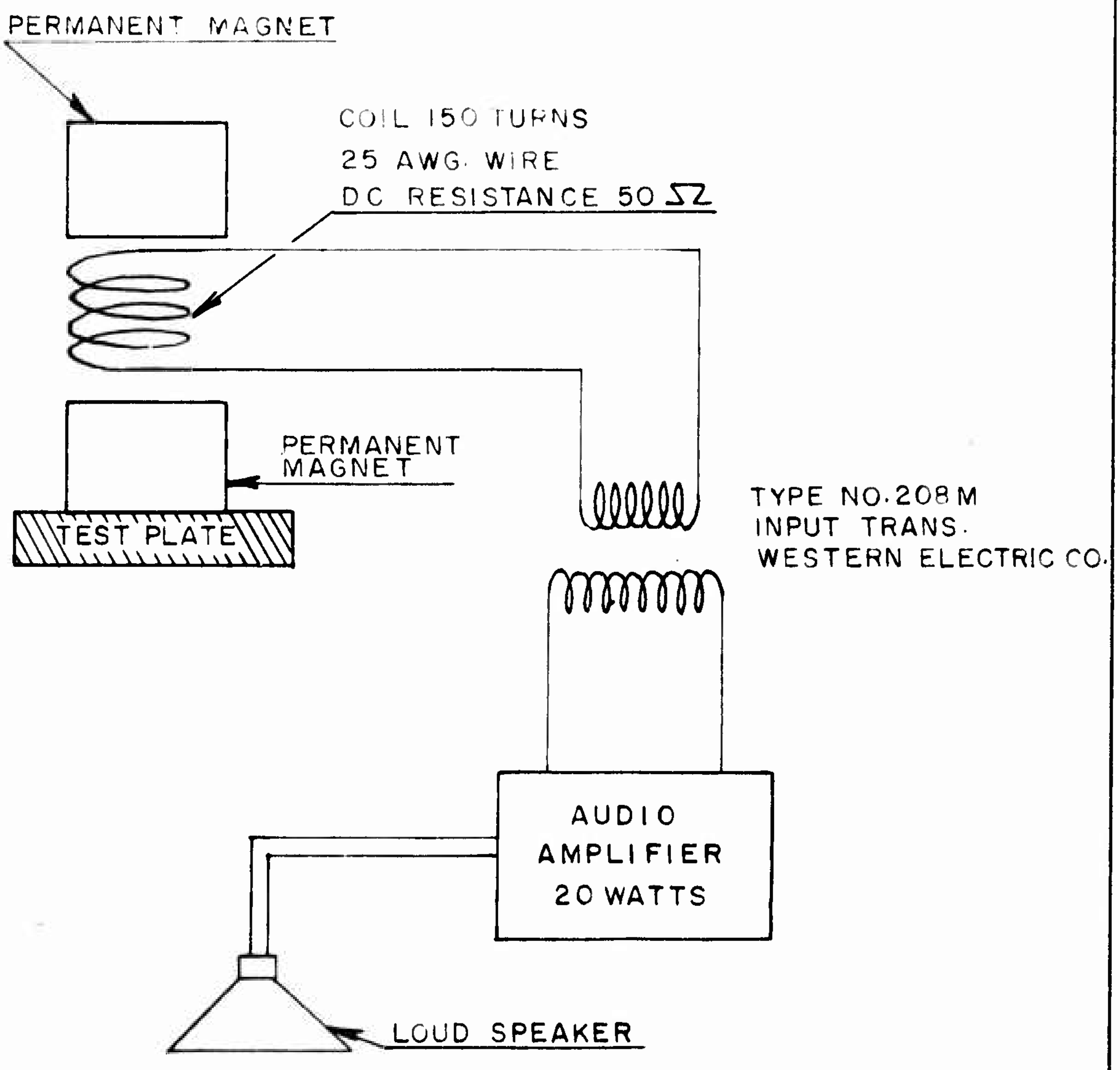


Figure 30

Apparatus used in sonic crack detection.

105159-4A
MR 207A



CRACK DETECTION APPARATUS
SCHEMATIC DIAGRAM

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FK
GY

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Figure 31